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# Software Solutions to Problems on Heat Transfer

## Boiling and Condensation

Dr. M. Thirumaleshwar

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M. Thirumaleshwar

# Software Solutions to Problems on Heat Transfer

## Boiling and Condensation

## (Pool Boiling and Flow Boiling, Condensation on Vertical plates and Cylinders, outside of Horizontal cylinders, Horizontal Tube Banks in a vertical tier, inside horizontal tubes etc.)

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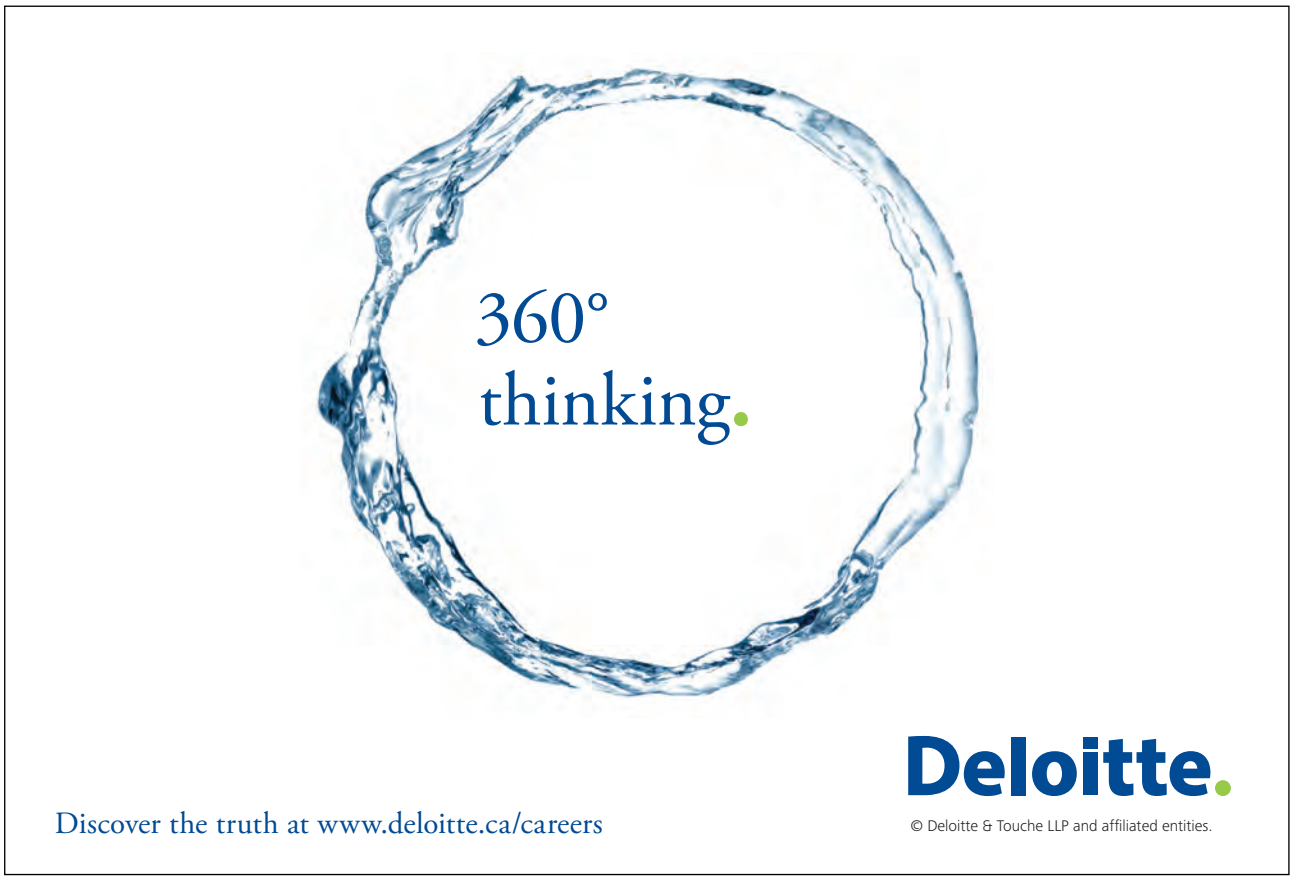


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# Preface to Vol. 3

This is Vol. 3 of the book **"Software Solutions to Problems on Heat Transfer".**

In Vol. 1, problems on various aspects of CONDUCTION heat transfer were solved with Mathcad, EES, FEHT and EXCEL.

Vol. 2 contained solved problems on the topics of CONVECTION (i.e. Forced convection, Natural or Free convection).

**Present Vol. viz. BOILING & CONDENSATION contains problems solved on following sub-topics:**

**Vol. 3: BOILING & CONDENSATION:**

**3.1. Boiling heat transfer:**

3.1. Boiling heat transfer Equation summary

Problems on: Pool Boiling and Flow Boiling

Problems solved with Mathcad

Problems solved with EES

Problems solved with EXCEL

**3.2. Condensation heat transfer:**

3.2. Condensation heat transfer Equation summary

Problems on: Condensation on Vertical plates and Cylinders, outside of Horizontal cylinders, Horizontal Tube Banks in a vertical tier, inside horizontal tubes etc.

Problems solved with Mathcad

Problems solved with EES

Problems solved with EXCEL

References

**Here also, problems are solved using the popular software, viz**. "Mathcad", "Engineering Equation Solver (EES)", and MS EXCEL spreadsheet**. Comments are included generously in the codes so that the logic behind the solutions is clear. An introductory chapter in Part-I gives a brief overview of the software used.**

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As in Vol. I and II, emphasis is given not only to solving a given problem but also to parametric analysis and graphical representation of results. Advantage of using Software to solve a variety of problems thus becomes evident. Also, problems with EXCEL spreadsheet are solved in greater details with relevant screen shots for immediate help to students, since EXCEL is available in practically every Personal Computer.

**Acknowledgements**: Firstly, I thank my students, since it is they who inspired me and motivated me. Next, my thanks are due to the authorities at St. Joseph Engineering College, for their constant encouragement.

Also, my sincere thanks to **Bookboon.com** for publishing this book on the Internet. **Ms. Sophie** and her editorial staff have to be specially mentioned for their cooperation, suggestions and support.

Finally, my heartfelt appreciation to **my wife, Kala,** for her unfailing and thoughtful support and encouragement.

M. Thirumaleshwar

*Author*

August 2013

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# About the Author

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenis) from University of Southampton, U.K. and Ph.D.(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Dept. in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

**Presently, he is Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.**

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

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He has also written and published three book-lets entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews
   (A guide book to Professional and Management students)

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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# About the Software used

Following three software are used while solving problems in this book:

1. Mathcad 2001 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and
3. Finite Element Heat Transfer (FEHT) (Ref: www.fchart.com)
4. MS EXCEL – (2007) Spreadsheet (Ref: Microsoft)

Trial versions of the first three software and detailed Instruction Manuals may be downloaded from the websites indicated. EXCEL is a very popular spreadsheet which comes bundled with MS OFFICE software, and is generally available in every computer.

**See Part-I of this book for brief introduction to these four software.**

While the information given there is enough to get going, for detailed instructions one should consult the respective Instruction manuals.

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# To the Student

*Dear Student:*

I would like to remind you that Heat Transfer is an important subject useful in many branches of engineering. It is also a subject in which you can score high marks in the examinations, since the question paper generally consists of derivations and numerical problems, almost in the ratio 50:50. Therefore, it requires that:

(i) you are thorough with the derivations, and
(ii) skillful in solving numerical problems.

To be thorough with derivations, you should refer to well known, standard Text books on the subject of Heat Transfer (See References at the end of this book). **And, to develop your skill in solving problems… well, that is where I think that this book will help you.**

This book contains solutions to problems on heat transfer using four popular softwares, viz. Mathcad, Engineering Equation Solver (EES), Finite Element Heat Transfer (FEHT), and EXCEL spreadsheet. Trial versions of Mathcad, EES and FEHT can be downloaded from the websites indicated. EXCEL, which is a part of MS OFFICE, is generally pre-installed in most of the Personal Computers. Problems are chosen from the University question papers and standard heat transfer Text books.

Use of Software in solving problems has many advantages:

1. It helps in logical thinking
2. Problems are solved quickly and accurately
3. Parametric solutions (or 'what-if' solutions) are obtained easily
4. Solutions can be presented in tabular or graphical form, very easily and quickly
5. Once a particular type of problem is solved, solving a similar problem with different data input becomes very easy
6. Ease of getting solutions to problems in tabular or graphical form creates further interest and curiosity on the subject in the minds of students and encourages them to be creative and work further

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**How to use this Book?**

You need not worry if you don't know about these softwares. Since each problem is solved systematically step by step, and is well commented, just reading through the solution will make the logic of the solution clear to you. That is the most important thing in solving the problems. ***Then, you must work out the problem yourself, by hand or using the software***. Of course, use of software has the above-mentioned advantages. *Simply reading the book won't do*. Have your favorite Text book nearby, in case you need to refer to it for any formulas or clarifications. There is no other 'easy method'.

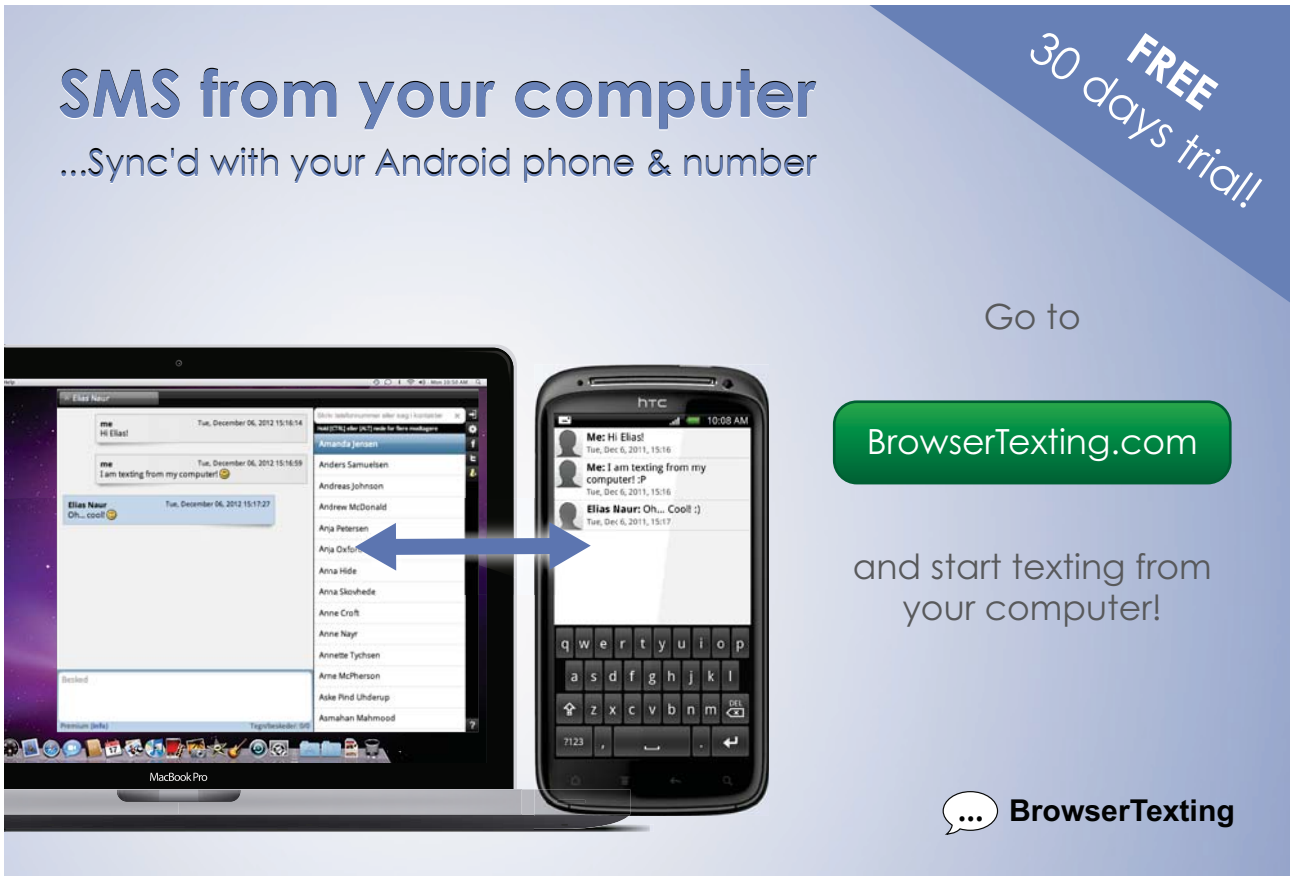
As they say, *'there is no gain without pain!'*

Lastly, I would like to tell you how greatly I enjoyed solving the problems presented in this book using the softwares mentioned.

I hope that you too will enjoy as much as I did in solving these problems and get benefitted.

Good Luck!

*Author*

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**Vol. 3. BOILING & CONDENSATION:**

**3.1. Boiling heat transfer:**

3.1. Boiling heat transfer Equation summary

Problems on: Pool Boiling and Flow Boiling

Problems solved with Mathcad

Problems solved with EES

Problems solved with EXCEL

**3.2. Condensation heat transfer:**

3.2. Condensation heat transfer Equation summary

Problems on: Condensation on Vertical plates and Cylinders, outside of Horizontal cylinders, Horizontal Tube Banks in a vertical tier, inside horizontal tubes etc.

Problems solved with Mathcad

Problems solved with EES

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2A1.2. Flow across Cylinders and Spheres

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2A2.5. Natural convection from Finned surfaces

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References

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4. About MS EXCEL

To the Student

**Vol. 1. CONDUCTION**

**1. Conduction Equation summary**

1A. Fourier's Law, heat conduction equation and Multi-mode heat transfer

1B. Thermal resistance concept , heat transfer in Slabs

1C.Heat transfer in Cylindrical and Spherical systems

1D. Critical radius problem

1E. Heat transfer with Fins

1F. Conduction with heat generation

1G. Transient conduction (Lumped system analysis, Heisler charts, Semi-infinite slabs etc.)

1H. Two-dimensional conduction – Shape factor

1I. Numerical Methods in heat conduction

- 1IA. One dimensional Steady State Conduction
- 1IB. Two dimensional Steady State Conduction
- 1IC. One dimensional Transient Conduction
- 1ID. Two dimensional Transient Conduction

References

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# 3 Boiling And Condensation

**Learning objectives:**

1. In Chapter 2, while dealing with convection (either Natural or Forced), the fluid involved was homogeneous and in single phase.
2. But, there are many important practical cases which involve heat transfer with a change of phase of the fluid, e.g. boiling where the liquid changes to vapour and condensation where the vapour condenses into a liquid.
3. Some of the applications of boiling and condensation are:
   i) Evaporators and condensers of a vapour compression refrigerating system
   ii) Boilers and condensers of a steam power plant
   iii) Reboilers and condensers of distillation columns of cryogenic and petrochemical plants
   iv) Cooling of nuclear reactors and rocket motors
   v) Process heating and cooling etc.
4. Unique features of boiling and condensation are:
   i) heat transfer, practically at a constant temperature, because of change of phase
   ii) latent heat and surface tension come into play in addition to buoyancy driven flow effects, resulting in larger heat transfer rates and heat transfer coefficients compared to the usual free or forced convection
   iii) *high heat transfer rates* with small temperature difference
5. We have mostly empirical relations for Boiling and Condensation. We will also need properties of Water and steam (at 1 atm. and sat. conditions), since in most of the cases we deal with water. Of course, there are other cases where boiling or condensation of other fluids, such as refrigerants or cryogenic fluids also have to be dealt with.
6. We will solve problems with these empirical relations and the functions for properties of water, written in EES, Mathcad or EXCEL.

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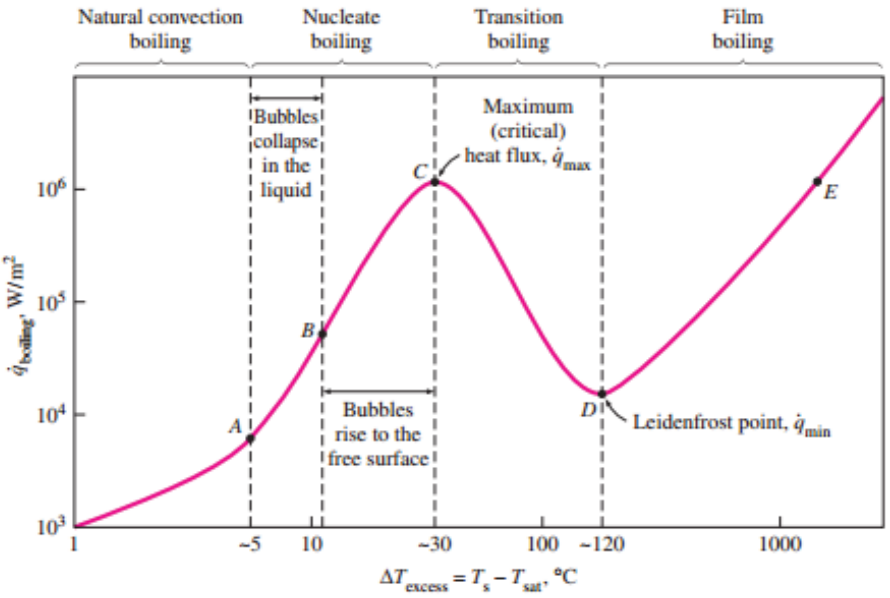
## 3.1 Boiling:

**Formulas used:**

1. **Boiling regimes and boiling curve: (Ref. 2)**

**For Water at 1 atm:**




In general, four different boiling regimes are observed depending upon the *excess temperature* ($\Delta T_e$) imposed, viz.

i) natural convection boiling ($\Delta T_e$ upto about 5 deg.C)
ii) nucleate boiling ($\Delta T_e$ from 5 deg to about 30 deg. C)
iii) transition boiling ($\Delta T_e$ from 30 deg to about 120 deg. C), and
iv) film boiling ($\Delta T_e$ beyond 120 deg. C)

---

2. **Heat transfer correlations for pool boiling: (Ref: 1)**

**2.1 Natural convection boiling regime**:( i.e. up to an excess temperature of about 5 deg. C). In this regime, the correlations already presented in the previous chapter on 'Natural (or, Free) convection' may be used.

**2.2 Nucleate boiling regime:** (i.e. excess temperature varying from about 5 deg. up to about 30 deg. C).

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Correlation proposed by Rohsenow in 1952, is the most widely used one, for heat flux in the nucleate boiling regime:

$$q_{nucleate} = \mu_L \cdot h_{fg} \cdot \left[\frac{g \cdot (\rho_L - \rho_V)}{\sigma}\right]^{\frac{1}{2}} \cdot \left[\frac{C_{pL} \cdot (T_s - T_{sat})}{C_{sf} \cdot h_{fg} \cdot Pr_L^{\,n}}\right]^3 \quad W/m2.....(11.5)$$

where, $q_{nucleate}$ = nucleate boiling heat flux, $W/m^2$
$\mu_L$ = viscosity of liquid, kg/ (m.s)
$h_{fg}$ = enthalpy of vapourization, J/kg
g = gravitational acceleration, $m/s^2$
$\rho_L$ = density of liquid, $kg/m^3$
$\rho_V$ = density of vapour, $kg/m^3$
$C_{pL}$ = Sp. Heat of liquid, J/(kg.C)
σ = surface tension of liquid – vapour interface, N/m
$T_s$ = surface temperature of heater, deg.C
$T_{sat}$ = saturation temperature of fluid, deg.C
$C_{sf}$ = a constant depending upon the specific surface-fluid combination
$Pr_L$ = Prandtl number of liquid
n = 1 for water, and 1.7 for all other liquids

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Subscripts L and V refer to liquid and vapour respectively.

Experiments show that nucleate boiling heat flux is not very much dependent on the geometry or orientation of the heater surface.

**Therefore, the correlation given above is valid for flat plates, cylinders and other geometries.**

**Since water is one of the most common fluids used, it is useful to have its surface tension and the constant Csf for water – surface combination, readily available.**

Surface tension and latent heat of water at a few temperatures are given in Table 11.1 below:

| Sat. temp. (Tsat), deg.C | Surface tension (σ), N/m | Latent heat (hfg), kJ/kg |
|---|---|---|
| 0 | 0.0755 | 2500.8 |
| 20 | 0.0729 | 2453.7 |
| 40 | 0.0695 | 2406.2 |
| 60 | 0.0661 | 2357.9 |
| 80 | 0.0627 | 2308.3 |
| 100 | 0.0589 | 2256.7 |
| 150 | 0.0487 | 2113.4 |
| 200 | 0.0378 | 1939.3 |
| 250 | 0.0261 | 1714.7 |
| 300 | 0.0143 | 1406.2 |
| 350 | 0.0036 | 916.1 |
| 374 | 0.0 | 0.0 |

**Table 11.1:** σ and $h_{fg}$ for water

**Also, surface tension of water (σ) can be quickly determined by the following equation:**

$$\sigma = 0.0808 * (1 - 0.00267 * T), \text{ N/m where T is in deg. C}$$

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Experimentally determined values of constant $C_{sf}$ for a few liquid-surface combinations are given in Table 11.2:

| **Fluid and surface** | **$C_{sf}$** |
|---|---|
| **Water-copper:** | |
| Scored surface | 0.0068 |
| Polished surface | 0.0130 |
| **Water-stainless steel:** | |
| Teflon coated surface | 0.0058 |
| Ground & polished surface | 0.0068 |
| Mechanically polished surface | 0.0130 |
| Chemically etched surface | 0.0130 |
| **Water-brass** | 0.0060 |
| **Water-nickel** | 0.0060 |
| **Water-platinum** | 0.0130 |
| **n-pentane-copper:** | |
| Lapped surface | 0.0049 |
| Polished surface | 0.0154 |
| **n-pentane-chromium** | 0.0150 |
| **Ethyl alcohol-chromium** | 0.0027 |

**Table 11.2:** $C_{sf}$ for a few liquid-surface combinations

Note that Rohsenow eqn. (11.5) is applicable for clean surfaces and for relatively smooth surfaces.

**To calculate the heat flux in nucleate boiling, Collier recommends** the following eqn. which is simpler to use as compared to eqn. (11.5):

$$q_{nucleate} = 0.000481 \cdot \Delta T_e^{3.33} \cdot P_{cr}^{2.3} \cdot \left[ 1.8 \cdot \left( \frac{P}{P_{cr}} \right)^{0.17} + 4 \cdot \left( \frac{P}{P_{cr}} \right)^{1.2} + 10 \cdot \left( \frac{P}{P_{cr}} \right)^{10} \right]^{3.33} \quad W/m^2 ....(11.7)$$

where $\Delta T_e$ is the excess temp. in deg. C, P is the operating pressure in atm., $P_{cr}$ is the critical pressure in atm.

**Based on Russian literature, following calculation formulas are recommended specifically for water in nucleate boiling**, in the pressure range 0.2–100 ata:

$$h_{nucleate} = 3.133 \cdot q^{0.7} \cdot P^{0.15} \quad W/(m^2.C) ...\text{for water}..(11.10,a)$$

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and,

$$h_{nucleate} = 45.054 \cdot \Delta T^{2.33} \cdot P^{0.5} \quad W/(m^2.C)....\text{for water.(11.10,b)}$$

In the above eqns. q is the heat flux in $W/m^2$, P is the pressure in bar, and $\Delta T$ is the excess temp. in deg.C.

**Peak (or, maximum) heat flux in nucleate pool boiling:**

Leinhard and Dhir (1973) give the following correlation for peak heat flux in nucleate pool boiling:

$$q_{max} = C_o \cdot h_{fg} \cdot \rho_V \left[ \frac{\sigma \cdot g \cdot (\rho_L - \rho_V)}{\rho_V^2} \right]^{\frac{1}{4}} \quad W/m^2.....(11.11)$$

where $C_o = 0.149$ for a large horizontal surface

and, $C_o = 0.116$ for a large horizontal cylinder

**Unlike the nucleate boiling flux, peak heat flux depends on heater geometry and orientation.**

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Another relation for **peak heat flux on horizontal cylinders**, which fits experimental data very well, is presented by Sun and Lienhard:

$$\frac{q_{max}}{q_{maxF}} = 0.89 + 2.27 \cdot \exp\left(-3.44 \cdot \sqrt{R'}\right) \quad W/m^2 \text{...for } 0.15 < R' < 3.47 \text{.....(11.12, a)}$$

$$\frac{q_{max}}{q_{maxF}} = 0.894 \quad W/m^2 \text{...for } R' > 3.47 \text{.....(11.12, b)}$$

where R′ is a dimensionless radius defined as:

$$R = R \cdot \left[\frac{g \cdot (\rho_L - \rho_V)}{\sigma}\right]^{\frac{1}{2}}$$

and $q_{maxF}$ is the peak heat flux on an infinite horizontal plate, given as:

$$q_{maxF} = 0.131 \cdot \sqrt{\rho_V} \cdot h_{fg} \cdot \left[\sigma \cdot g \cdot (\rho_L - \rho_V)\right]^{\frac{1}{4}} \quad W/m^2 \text{....for infinite horizontal plate.....(11.13)}$$

**Cengel (Ref. 2) gives following relation of Zuber and a Table due to Lienhard et al for Max. heat flux:**

$$\dot{q}_{max} = C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \qquad \textbf{(10-3)}$$

**TABLE 10–4**

Values of the coefficient $C_{cr}$ for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

| Heater Geometry | $C_{cr}$ | Charac. Dimension of Heater, $L$ | Range of $L^*$ |
|---|---|---|---|
| Large horizontal flat heater | 0.149 | Width or diameter | $L^* > 27$ |
| Small horizontal flat heater[1] | $18.9K_1$ | Width or diameter | $9 < L^* < 20$ |
| Large horizontal cylinder | 0.12 | Radius | $L^* > 1.2$ |
| Small horizontal cylinder | $0.12L^{*-0.25}$ | Radius | $0.15 < L^* < 1.2$ |
| Large sphere | 0.11 | Radius | $L^* > 4.26$ |
| Small sphere | $0.227L^{*-0.5}$ | Radius | $0.15 < L^* < 4.26$ |

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

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**Minimum heat flux:**

This occurs at point D in Fig. (11.2); minimum heat flux represents the lower limit of heat flux in film boiling. For a **large, horizontal plate**, Zuber derived the following relation (modified by Berenson in 1961) for minimum heat flux:

$$q_{min} = 0.09 \cdot \rho_V \cdot h_{fg} \cdot \left[ \frac{\sigma \cdot g \cdot (\rho_L - \rho_V)}{(\rho_L + \rho_V)^2} \right]^{\frac{1}{4}} \quad W/m^2 .....(11.15)$$

**Film boiling:**

Heat transfer coefficient in stable film boiling regime on a horizontal cylinder or sphere is predicted by Bromley's correlation:

$$h_{film} = C_o \cdot \left[ \frac{g \cdot \rho_V \cdot (\rho_L - \rho_V) \cdot h'_{fg} \cdot k_V^3}{\mu_V \cdot (T_s - T_{sat}) \cdot L} \right]^{\frac{1}{4}} \quad W/(m^2.C).....(11.16)$$

where $h'_{fg} = h_{fg} + 0.4 \cdot C_{pV} \cdot (T_s - T_{sat})$

$C_o$ = 0.62 and L = D ....for a horizontal cylinder

$C_o$ = 0.67 and L = D ....for a sphere

For a very large diameter tube (diameter D) or a horizontal surface, eqn. (11.16) is valid, with the following value for $C_o$ (Westwater and Breen, 1962):

$$C_o = \left( 0.59 + \frac{0.69 \cdot \lambda}{D} \right) \quad \text{and,} \quad L = \lambda$$

and, $$\lambda = 2 \cdot \pi \cdot \left[ \frac{\sigma}{g \cdot (\rho_L - \rho_V)} \right]^{\frac{1}{2}}$$

Note that *for a horizontal surface*, $C_o = 0.59$, since $D \rightarrow \infty$

Vapour properties in eqn. (11.16) are evaluated at the *mean film temperature*, $T_f = (T_s + T_{sat})/2$, and *at a pressure $P_{sat}$ corresponding to temp $T_{sat}$.*

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As stated earlier, during stable film boiling, at high temperatures (> 300 C), thermal radiation effects become significant and Bromley suggested using an overall heat transfer coefficient given by:

$$h = h_{film} + 0.75 \cdot h_{rad} \quad \text{....(11.17)}$$

and, $h_{rad}$ is given by:

$$h_{rad} = \frac{\sigma \cdot \varepsilon \cdot \left( T_s^{\,4} - T_{sat}^{\,4} \right)}{\left( T_s - T_{sat} \right)} \quad \text{W/(m}^2\text{.C).....(11.18)}$$

where $\sigma = 5.67 \cdot 10^{-8}$ W/(m$^2$.K$^4$)....Stefan-Boltzmann const.

and, ε is the emissivity of the heated surface

**Also, remember that in eqn. (11.18), the temperatures Ts and Tsat must be in Kelvin.**

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Heat flux in stable film boiling is easily calculated, once the heat transfer coeff. is determined. i.e.

$$q_{film} = h \cdot (T_s - T_{sat}) \quad W/m^2 .....(11.19)$$

---

**Simplified correlations for boiling with water:**

Since water is one of the most commonly used fluids in practice, it is useful to have some simplified correlations for boiling water.

Jakob and Hawkins (1957) presented following simple relations for water boiling at atmospheric pressure on submerged surfaces:

| Type of surface | Range of validity (kW/m2) | h (W/m2.K) |
|---|---|---|
| Horizontal: | $q_s < 15.8$ | $1040 \times (\Delta T_e)^{1/3}$ |
| | $15.8 < q_s < 236$ | $5.56 \times (\Delta T_e)^3$ |
| ***Vertical:*** | $q_s < 3.15$ | $539 \times (\Delta T_e)^{1/7}$ |
| | $3.15 < q_s < 63.1$ | $7.95 \times (\Delta T_e)^3$ |

**Table 11.4:** Simplified relations for boiling heat transfer coeff. for water at one atm. pressure

**Heat transfer coefficients at pressures other than atmospheric** may be calculated using the following empirical equation:

$$h_p = h_a \cdot \left(\frac{p}{p_a}\right)^{0.4} \quad ...(11.20)$$

where, $h_p$ = heat transfer coeff. at any pressure p,

$h_a$ = heat transfer coeff. at pressure $p_a$ (= 1 atm.) from Table 11.4.

==========

**Note: All the above relations are for submerged bodies in pool boiling.**

Now, let us consider 'Flow boiling', where the fluid is in motion while boiling occurs:

**Flow Boiling:**

In flow boiling, a fluid is forced to move over a heated surface while the phase change occurs. Therefore, combined effects of natural/forced convection and pool boiling come into play.

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Flow boiling is classified as:

i) External flow boiling, and
ii) Internal flow boiling

**(i) External flow boiling:**

In external flow boiling, flow occurs over the surface of a plate or cylinder; there are the flow regimes similar to that in pool boiling, but due to the effect of flow velocity, both the nucleate boiling heat flux and the critical heat flux get enhanced. See Fig. 11.5. For water in external flow boiling, critical heat flux value as high as 35 MW/m$^2$ has been obtained (as compared to the value of 1.3 MW/m$^2$ in pool boiling at one atm.).

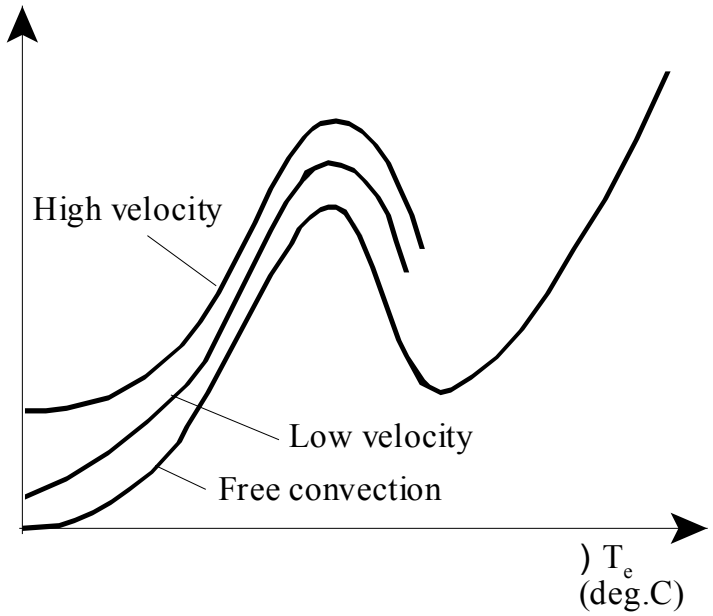


**Fig. 11.5** Effet of flow veloity in external flow boiling

For cross flow over a cylinder of diameter D, Lienhard and Eichhorn have given following correlations for max. (or critical) heat flux, depending upon whether the fluid velocity is 'low' or 'high'.

Criterion to determine if the velocity is low or high is:

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} > \left[ \left( \frac{0.275}{\pi} \right) \cdot \left( \frac{\rho_L}{\rho_V} \right)^{\frac{1}{2}} + 1 \right] \quad \text{.....low velocity}$$

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and,

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} < \left(\frac{0.275}{\pi}\right) \cdot \left(\frac{\rho_L}{\rho_V}\right)^{\frac{1}{2}} + 1 \qquad \text{.....high velocity}$$

**Correlation for Low velocity:**

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} = \frac{1}{\pi} \cdot \left[1 + \left(\frac{4}{We_D}\right)^{\frac{1}{3}}\right] \qquad \text{.....(11.21)}$$

**Correlation for High velocity:**

$$\frac{q_{max}}{\rho_V \cdot h_{fg} \cdot V} = \frac{\left(\frac{\rho_L}{\rho_V}\right)^{\frac{3}{4}}}{169 \cdot \pi} + \frac{\left(\frac{\rho_L}{\rho_V}\right)^{\frac{1}{2}}}{19.2 \cdot \pi \cdot We_D^{\frac{1}{3}}} \qquad \text{....(11.22)}$$

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Here, V is he fluid velocity and $We_D$ is the **Weber number**, defined as the ratio of inertia forces to surface tension forces, i.e.

$$We_D = \frac{\rho V \cdot V^2 \cdot D}{\sigma} \quad ....(11.23)$$

**(ii) Internal flow boiling:**

Internal forced convection boiling refers to flow inside a tube. This is more complicated since, now, there is no free surface for the vapour to escape and results in two phase flow inside the tube. There are different flow regimes occurring inside the tube depending upon the 'quality' of the fluid. ('Quality' is defined as the ratio of mass of vapour to the total mass of fluid at a given location). This is illustrated in Fig. 11.6, which also shows a qualitative graph of variation of heat transfer coeff. with local quality.

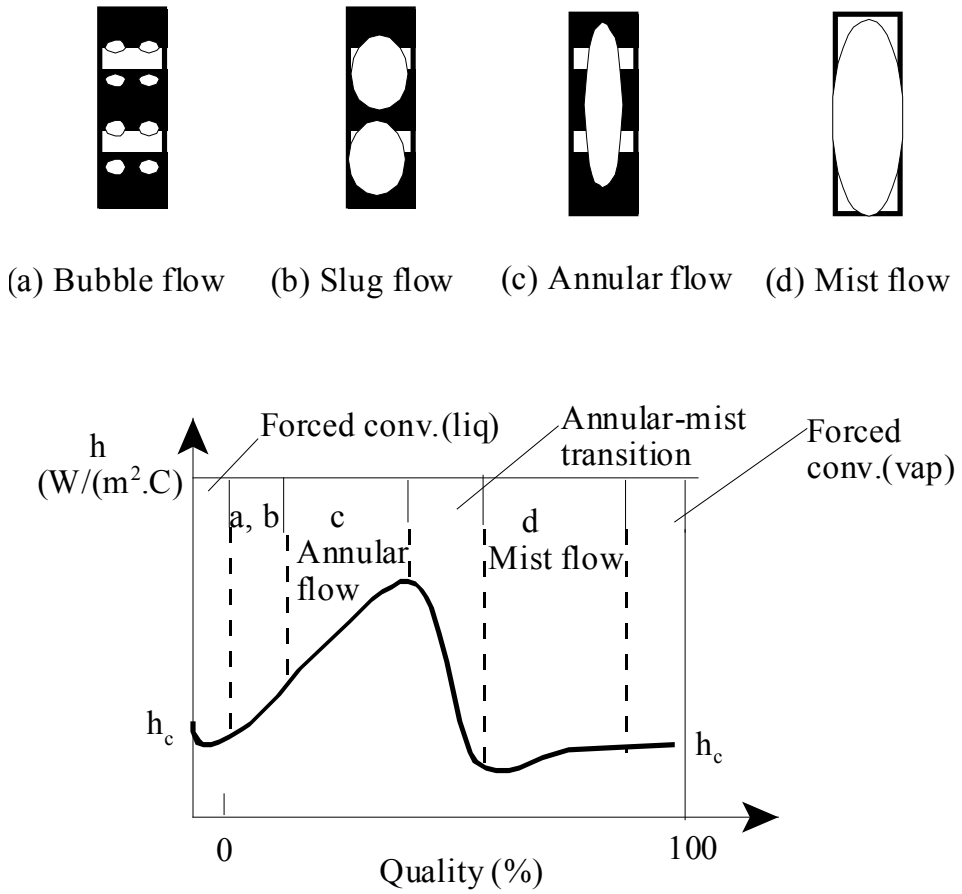


**Fig. 11.6** Flow regimes and heat transfer coefficient inforced convection flow in a vertical tube

Consider a fluid, at a temperature below its boiling point, entering a vertical, heated tube. Progressive vapourization occurs along the length of the tube and the 'quality' increases. Upto a short distance from the inlet, heat transfer coeff. for the single phase fluid may be predicted using the Dittus-Boelter equation.

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***Bubble – flow regime:*** Soon, the bulk temperature reaches the saturation point, and bubbles are formed at the nucleation sites on the wall and are carried into the main stream, as in nucleate boiling. This is known as the 'bubble flow regime' (see fig. 11.6(a)) and the heat transfer coeff. increases. **Heat transfer coeff. in this range can be predicted by superimposing the liquid-forced convection and nucleate pool boiling equations.**

***Slug – flow regime:*** Further along the distance, vapour fraction increases and individual bubbles agglomerate and slugs of vapour are formed. This regime is known as 'slug flow regime'. See Fig. 11.6(b). Fluid velocity increases and since the slugs of vapour are compressible, flow oscillations may occur. Mass fraction of vapour in this regime is around 1%, but volume fraction of vapour may be even upto 50%. **In this regime also, heat transfer coeff. may be calculated by superimposing the liquid-forced convection and nucleate pool boiling equations.** Heat transfer coeff. increases because of increased velocity.

***Annular – flow regime:*** As the fluid progresses further up the tube, quality increases due to further addition of heat and vapour forms the core and a film of liquid flows on the inner wall surface. Vapour core travels at a higher velocity than the liquid and vapours are formed primarily at the liquid-vapour interface and not at the wall surface. Quality in this flow regime may be upto 25%. See Fig. 11.6(c).

***Transition – flow regime:*** Now, as the quality increases, there is a sudden drop in the value of heat transfer coefficient. Heat flux at this point is known as 'critical heat flux'. This is the point of dryout. This sudden drop happens since the liquid film at the wall is now replaced by a vapour film, which has a poor thermal conductivity. *There may be sharp increase in the wall temperature and even burn-out may occur.*

***Mist – flow regime:*** Now, the tube is fully occupied by the vapour, which may contain droplets of liquid. This is known as mist-flow regime. See Fig. 11.6(d). Heat transfer from the wall is to the vapour directly, and then from the vapour, heat is transferred to the droplets of liquid contained in the vapour.

**From the annular-flow regime onwards, prediction of heat transfer coefficient is a little difficult and uncertain due to problems of two phase flow.**

**Two phase flow is beyond the scope of this book.**

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**Correlations to find out heat transfer coefficient in *nucleate flow boiling* only are presented below:**

**Correlations for nucleate flow boiling:**

Rosenhow and Griffith (1955) have suggested that total heat flux be calculated by adding the nucleate pool boiling flux (from eqn. (11.5)) and the forced convection effect (from Dittus-Boelter eqn. with the coeff. 0.023 replaced by 0.019),

i.e.

$$q_{total} = q_{nucleate} + q_{forced\_convection} \quad \text{....(11.24)}$$

For forced convection flow **inside vertical tubes**, following correlation is recommended:

$$h = 2.54 \cdot \left(\Delta T_e\right)^3 \cdot e^{\frac{p}{1.551}} \quad W/(m^2.K)\text{....(11.25)}$$

where, $\Delta T_e = T_s - T_{sat}$ , and p = pressure in mega pascals.

Above eqn. is valid for the pressure range of 5 to 170 bar.

**For horizontal tubes**, McAdams et.al. suggest following relation for low pressure boiling water:

$$q_{total} = q_{conv} + q_{boiling}$$

$q_{conv}$ is calculated using:

$$Nu = 0.019 \cdot Re^{0.8} \cdot Pr^{0.4} \quad \text{..Nusselts No. =( h * D) / k\_liq}$$

$$Re = \frac{G \cdot (1 - x) \cdot D}{\mu_{liq}} \quad \text{where x = dryness, G = mass velocity (kg/m^2.s)}$$

$$q_{boiling} = 2.253 \cdot \Delta T_e^{3.96} \quad \text{W/m^2...for 0.2 < P < 0.7 MPa}$$

$$q_{boiling} = 283.2 \cdot P^{\frac{4}{3}} \cdot \Delta T_e^{3} \quad \text{W/m^2....for 0.7 < P < 4 MPa}$$

Here, the pressure P is in mega-Pascals.

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**Prob.3.1.1:** Water at a pressure of one atm. is boiled in a polished copper pan, 300 mm dia. If the surface temperature of the pan is 110 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. heat flux.

**We shall solve this problem with Mathcad.**

Since Mathcad does not have built-in functions for properties of Water, we will have to write them.

Remember that we wrote a few Functions in Mathcad for properties of sat. water earlier (See prob. 2A2.2.4, for example). However, there we wrote Functions only for sat.water, liquid; and, the Functions were written using the curve-fit equations.

Now, for a change, we will use interpolation from Data Tables for Sat. water (Ref: Incropera, Ref. 3) and write Functions for both sat. liquid and sat. vapour.

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**Interpolation in Mathcad is very simple:**

The format is:

Y = linterp (Vx,Vy, X), where

Vx is the vector of x-values
Vy is the vector of y-values
X is the value of X at which the y-value is desired
Y is the value of interpolated y value

---

First, properties given in data Table from Incropera (say, from an EXCEL file) are copied to Mathcad as two Matrices M1 and M2 as shown:

Units for various quantities in the following Table are:

**Units:** T(K), v_f *10^3 (m^3/kg), v_g (m^3/kg), h_fg (kJ/kg), cp_f(kJ/kg.K), cp_g (kJ/kg.K), mu_f *10^6 (N.s/m^2), mu_g*10^6 (N.s/m^2), k_f*10^3 (W/m.K), k_g*10^3, (W/m.K), Pr_f, sigma_f*10^3 (N/m), beta_f*10^6 (1/K):

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M1 :=

| T (K) | v_f | v_g | h_fg | cp_f | cp_g |
|---|---|---|---|---|---|
| 273.15 | 1 | 206.3 | 2502 | 4.217 | 1.854 |
| 275 | 1 | 181.7 | 2497 | 4.211 | 1.855 |
| 280 | 1 | 130.4 | 2485 | 4.198 | 1.858 |
| 285 | 1 | 99.4 | 2473 | 4.189 | 1.861 |
| 290 | 1.001 | 69.7 | 2461 | 4.184 | 1.864 |
| 295 | 1.002 | 51.94 | 2449 | 4.181 | 1.868 |
| 300 | 1.003 | 39.13 | 2438 | 4.179 | 1.872 |
| 305 | 1.005 | 29.74 | 2426 | 4.178 | 1.877 |
| 310 | 1.007 | 22.93 | 2414 | 4.178 | 1.882 |
| 315 | 1.009 | 17.82 | 2402 | 4.179 | 1.888 |
| 320 | 1.011 | 13.98 | 2390 | 4.18 | 1.895 |
| 325 | 1.013 | 11.06 | 2378 | 4.182 | 1.903 |
| 330 | 1.016 | 8.82 | 2366 | 4.184 | 1.911 |
| 335 | 1.018 | 7.09 | 2354 | 4.186 | 1.92 |
| 340 | 1.021 | 5.74 | 2342 | 4.188 | 1.93 |
| 345 | 1.024 | 4.683 | 2329 | 4.191 | 1.941 |
| 350 | 1.027 | 3.846 | 2317 | 4.195 | 1.934 |
| 355 | 1.03 | 3.18 | 2304 | 4.199 | 1.968 |
| 360 | 1.034 | 2.645 | 2291 | 4.203 | 1.983 |
| 365 | 1.038 | 2.212 | 2278 | 4.209 | 1.999 |
| 370 | 1.041 | 1.861 | 2265 | 4.214 | 2.017 |
| 373.15 | 1.044 | 1.679 | 2257 | 4.217 | 2.029 |
| 375 | 1.04 | 1.574 | 2252 | 4.22 | 2.036 |
| 380 | 1.049 | 1.337 | 2239 | 4.226 | 2.057 |
| 400 | 1.067 | 0.731 | 2183 | 4.256 | 2.158 |
| 420 | 1.088 | 0.425 | 2123 | 4.302 | 2.291 |
| 440 | 1.11 | 0.261 | 2059 | 4.36 | 2.46 |
| 460 | 1.137 | 0.167 | 1989 | 4.44 | 2.68 |
| 480 | 1.167 | 0.111 | 1912 | 4.53 | 2.94 |
| 500 | 1.203 | 0.0766 | 1825 | 4.66 | 3.27 |
| 520 | 1.244 | 0.0525 | 1730 | 4.84 | 3.7 |
| 540 | 1.294 | 0.0375 | 1622 | 5.08 | 4.27 |
| 560 | 1.355 | 0.0269 | 1499 | 5.43 | 5.09 |
| 580 | 1.433 | 0.0193 | 1353 | 6 | 6.4 |
| 600 | 1.541 | 0.0137 | 1176 | 7 | 8.75 |
| 620 | 1.705 | 0.0094 | 941 | 9.35 | 15.4 |
| 640 | 2.075 | 0.0057 | 560 | 26 | 42 |
| 645 | 2.351 | 0.0045 | 361 | 90 | $1.00 \cdot 10^{10}$ |
| 647.3 | 3.17 | 0.0032 | 0 | $1.00 \cdot 10^{10}$ | $1.00 \cdot 10^{10}$ |

M2 :=

| mu_f | mu_g | k_f | k_g | Pr_f | sigma_f |
|---|---|---|---|---|---|
| 1750 | 8.02 | 569 | 18.2 | 12.99 | 75.5 |
| 1652 | 8.09 | 574 | 18.3 | 12.22 | 75.3 |
| 1422 | 8.29 | 582 | 18.6 | 10.26 | 74.8 |
| 1225 | 8.49 | 590 | 18.9 | 8.81 | 74.3 |
| 1080 | 8.69 | 598 | 19.3 | 7.56 | 73.7 |
| 959 | 8.89 | 606 | 19.5 | 6.62 | 72.7 |
| 855 | 9.09 | 613 | 19.6 | 5.83 | 71.7 |
| 769 | 9.29 | 620 | 20.1 | 5.2 | 70.9 |
| 695 | 9.49 | 628 | 20.4 | 4.62 | 70 |
| 631 | 9.69 | 634 | 20.7 | 4.16 | 69.2 |
| 577 | 9.89 | 640 | 21 | 3.77 | 68.3 |
| 528 | 10.09 | 645 | 21.3 | 3.42 | 67.5 |
| 489 | 10.29 | 650 | 21.7 | 3.15 | 66.6 |
| 453 | 10.49 | 656 | 22 | 2.88 | 65.8 |
| 420 | 10.69 | 660 | 22.3 | 2.66 | 64.9 |
| 389 | 10.89 | 668 | 22.6 | 2.45 | 64.1 |
| 365 | 11.09 | 668 | 23 | 2.29 | 63.2 |
| 343 | 11.29 | 671 | 23.3 | 2.14 | 62.3 |
| 324 | 11.49 | 674 | 23.7 | 2.02 | 61.4 |
| 306 | 11.69 | 677 | 24.1 | 1.91 | 60.5 |
| 289 | 11.89 | 679 | 24.5 | 1.8 | 59.5 |
| 279 | 12.02 | 680 | 24.8 | 1.76 | 58.9 |
| 274 | 12.09 | 681 | 24.9 | 1.7 | 58.6 |
| 260 | 12.29 | 683 | 25.4 | 1.61 | 57.6 |
| 217 | 13.05 | 688 | 27.2 | 1.34 | 53.6 |
| 185 | 13.79 | 688 | 29.8 | 1.16 | 49.4 |
| 162 | 14.5 | 682 | 31.7 | 1.04 | 45.1 |
| 143 | 15.19 | 673 | 34.6 | 0.95 | 40.7 |
| 129 | 15.88 | 660 | 38.1 | 0.89 | 36.2 |
| 118 | 16.59 | 642 | 42.3 | 0.86 | 31.6 |
| 108 | 17.33 | 621 | 47.5 | 0.84 | 26.9 |
| 101 | 18.1 | 594 | 54 | 0.86 | 22.1 |
| 94 | 19.1 | 563 | 63.7 | 0.9 | 17.3 |
| 88 | 20.4 | 528 | 76.7 | 0.99 | 12.8 |
| 81 | 22.7 | 497 | 92.9 | 1.14 | 8.4 |
| 72 | 25.9 | 444 | 114 | 1.52 | 4.5 |
| 59 | 32 | 367 | 155 | 4.2 | 0.8 |
| 54 | 37 | 331 | 178 | 12 | 0.1 |
| 45 | 45 | 238 | 238 | $1.00 \cdot 10^{10}$ | 0 |

Now, each column is extracted as a vector and then the interpolation function 'linterp' is used for linear interpolation.

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For example, zeroth column of M1 is Temp in Kelvin. It is extracted as:

$$TempK := M1^{\langle 0 \rangle}$$

This means: $0^{th}$ column of M1 is assigned as a vector called TempK. (Note: In Mathcad, by default, the column and row numbers start from 0 and *not* 1).

Similarly, v_f, the specific volume of liquid, is in the $1^{st}$ column of M1. It is extracted as:

$$H2Ov\_f := M1^{\langle 1 \rangle}$$

which means that values of sp. vol. of liquid, which are in the $1^{st}$ column of M1 are read as a column vector H2Ov_f.

**Now, at any given temp T, value of v_f is obtained by linear interpolation, by writing:**

$$vf := linterp(TempK, H2Ov\_f, T) \cdot 10^{-3}$$

Similarly, we have vectors extracted for other properties:

$$TempK := M1^{\langle 0 \rangle} \quad H2Ov\_f := M1^{\langle 1 \rangle} \quad H2Ov\_g := M1^{\langle 2 \rangle} \quad H2Oh\_fg := M1^{\langle 3 \rangle}$$

$$H2Ocp\_f := M1^{\langle 4 \rangle} \quad H2Ocp\_g := M1^{\langle 5 \rangle} \quad H2Omu\_f := M2^{\langle 0 \rangle} \quad H2Omu\_g := M2^{\langle 1 \rangle}$$

$$H2Ok\_f := M2^{\langle 2 \rangle} \quad H2Ok\_g := M2^{\langle 3 \rangle} \quad H2OPr\_f := M2^{\langle 4 \rangle} \quad H2Osigma\_f := M2^{\langle 5 \rangle}$$

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For the property, β i.e. coeff. of vol. expansivity, values are available in the Table from T = 273.15 K up to T = 420 K. So, we separately extract them as two vectors:

| | Temp (K) | | beta_f * 10^6 (1/K) |
|---|---|---|---|
| | 273.15 | | −68.05 |
| | 275 | | −32.74 |
| | 280 | | 46.04 |
| | 285 | | 114.1 |
| | 290 | | 174 |
| | 295 | | 227.5 |
| | 300 | | 276.1 |
| | 305 | | 320.6 |
| | 310 | | 361.9 |
| | 315 | | 400.4 |
| | 320 | | 436.7 |
| | 325 | | 471.2 |
| TempKelvin := | 330 | H2Obeta_f := | 504 |
| | 335 | | 535.5 |
| | 340 | | 566 |
| | 345 | | 595.4 |
| | 350 | | 624.2 |
| | 355 | | 652.3 |
| | 360 | | 697.9 |
| | 365 | | 707.1 |
| | 370 | | 728.7 |
| | 373.15 | | 750.1 |
| | 375 | | 761 |
| | 380 | | 788 |
| | 400 | | 896 |
| | 420 | | 1010 |

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And, Mathcad Functions are written for different properties by interpolation, using these vectors, as explained earlier:

**Mathcad Functions for various properties are::**

**T (K) , beta_f (1/K) .:**

$$\text{beta\_f\_H2O}(\text{TempKelvin}, \text{H2Obeta\_f}, T) := \begin{cases} \text{return "T must be between 273.15 K and 420 K !!"} & \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 420 K !!"} & \text{if } T > 420 \\ \text{beta\_f} \leftarrow \text{linterp}(\text{TempKelvin}, \text{H2Obeta\_f}, T) \cdot 10^{-6} & \text{otherwise} \end{cases}$$

Ex: $\text{beta\_f\_H2O}(\text{TempKelvin}, \text{H2Obeta\_f}, 385) = 8.15 \times 10^{-4}$

---

**T (K) , v_f (m^3/kg) .:**

$$\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, T) := \begin{cases} \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T > 647.3 \\ \text{vf} \leftarrow \text{linterp}(\text{TempK}, \text{H2Ov\_f}, T) \cdot 10^{-3} & \text{otherwise} \end{cases}$$

Ex: $\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, 642) = 2.185 \times 10^{-3}$

---

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**T (K) , v_g (m^3/kg) .:**

$$vg\_H2O(TempK, H2Ov\_g, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!" if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!" if } T > 647.3 \\ vg \leftarrow \text{linterp}(TempK, H2Ov\_g, T) \text{ otherwise} \end{|}$$

Ex: $vg\_H2O(TempK, H2Ov\_g, 290) = 69.7$

---

**T (K) , h_fg (J/kg) .:**

$$h\_fg\_H2O(TempK, H2Oh\_fg, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!" if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!" if } T > 647.3 \\ h\_fg \leftarrow \text{linterp}(TempK, H2Oh\_fg, T)\cdot 10^{3} \text{ otherwise} \end{|}$$

Ex: $h\_fg\_H2O(TempK, H2Ov\_f, 642) = 2.185 \times 10^{3}$

---

**T (K) , cp_f (J/kg.K) .:**

$$cp\_f\_H2O(TempK, H2Ocp\_f, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!" if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!" if } T > 647.3 \\ cp\_f \leftarrow \text{linterp}(TempK, H2Ocp\_f, T)\cdot 10^{3} \text{ otherwise} \end{|}$$

Ex: $cp\_f\_H2O(TempK, H2Ocp\_f, 642) = 5.16 \times 10^{4}$

---

**T (K) , cp_g (J/kg.K) .:**

$$cp\_g\_H2O(TempK, H2Ocp\_g, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!" if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!" if } T > 647.3 \\ cp\_g \leftarrow \text{linterp}(TempK, H2Ocp\_g, T)\cdot 10^{3} \text{ otherwise} \end{|}$$

Ex: $cp\_g\_H2O(TempK, H2Ocp\_g, 642) = 4 \times 10^{12}$

---

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**T (K) , mu_f (kg/m.s) .:**

$$mu\_f\_H2O(TempK, H2Omu\_f, T) := \begin{cases} \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T > 647.3 \\ mu\_f \leftarrow \text{linterp}(TempK, H2Omu\_f, T) \cdot 10^{-6} & \text{otherwise} \end{cases}$$

Ex: $mu\_f\_H2O(TempK, H2Omu\_f, 642) = 5.7 \times 10^{-5}$

**T (K) , mu_g (kg/m.s) .:**

$$mu\_g\_H2O(TempK, H2Omu\_g, T) := \begin{cases} \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} & \text{if } T > 647.3 \\ mu\_g \leftarrow \text{linterp}(TempK, H2Omu\_g, T) \cdot 10^{-6} & \text{otherwise} \end{cases}$$

Ex: $mu\_g\_H2O(TempK, H2Omu\_g, 642) = 3.4 \times 10^{-5}$

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**T (K) , k_f (W/m.K) .:**

$$k\_f\_H2O(TempK, H2Ok\_f, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T > 647.3 \\ k\_f \leftarrow \text{linterp}(TempK, H2Ok\_f, T) \cdot 10^{-3} \text{ otherwise} \end{|}$$

Ex: $k\_f\_H2O(TempK, H2Ok\_f, 642) = 0.353$

---

**T (K) , k_g (W/m.K) .:**

$$k\_g\_H2O(TempK, H2Ok\_g, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T > 647.3 \\ k\_g \leftarrow \text{linterp}(TempK, H2Ok\_g, T) \cdot 10^{-3} \text{ otherwise} \end{|}$$

Ex: $k\_g\_H2O(TempK, H2Ok\_g, 642) = 0.164$

---

**T (K) , Pr_f .:**

$$Pr\_f\_H2O(TempK, H2OPr\_f, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T > 647.3 \\ Pr\_f \leftarrow \text{linterp}(TempK, H2OPr\_f, T) \text{ otherwise} \end{|}$$

Ex: $Pr\_f\_H2O(TempK, H2OPr\_f, 642) = 7.32$

---

**T (K) , sigma_f (N/m) .:**

$$sigma\_f\_H2O(TempK, H2Osigma\_f, T) := \begin{| l} \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T < 273.15 \\ \text{return "T must be between 273.15 K and 647.3 K !!"} \text{ if } T > 647.3 \\ sigma\_f \leftarrow \text{linterp}(TempK, H2Osigma\_f, T) \cdot 10^{-3} \text{ otherwise} \end{|}$$

Ex: $sigma\_f\_H2O(TempK, H2Osigma\_f, 642) = 5.2 \times 10^{-4}$

---

**We also need properties of Steam (i.e. water vapour) at 1 atm and different temperatures,** while solving problems on Film boiling heat transfer.

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So, let us write Mathcad Functions for properties of Steam at 1 atm as a function of temperature:

**First, get the properties of Steam at 1 atm from an EXCEL Table (Ref: Incropera, Ref. 3):**

**Properties of Water vap, i.e. Steam at 1 atm. (Ref: Incropera, p. 921):**

**Units:** T(K) , rho (kg/m^3), cp (kJ/kg.K), mu *10^7 (Ns/m^2), nu*10^6 (m^2/s), k*10^3 (W/m.K), alpha*10^6 (m^2/s), Pr:

$$M5 := \begin{array}{cccccccc} T & rho & cp & mu & nu & k & alpha & Pr \\ 380 & 0.5863 & 2.06 & 127.1 & 21.68 & 24.6 & 20.4 & 1.06 \\ 400 & 0.5542 & 2.014 & 134.4 & 24.25 & 26.1 & 23.4 & 1.04 \\ 450 & 0.4902 & 1.98 & 152.5 & 31.11 & 29.9 & 30.8 & 1.01 \\ 500 & 0.4405 & 1.985 & 170.4 & 38.68 & 33.9 & 38.8 & 0.998 \\ 550 & 0.4005 & 1.997 & 188.4 & 47.04 & 37.9 & 47.4 & 0.993 \\ 600 & 0.3652 & 2.026 & 206.7 & 56.6 & 42.2 & 57 & 0.993 \\ 650 & 0.338 & 2.056 & 224.7 & 66.48 & 46.4 & 66.8 & 0.996 \\ 700 & 0.314 & 2.085 & 242.6 & 77.26 & 50.5 & 77.1 & 1 \\ 750 & 0.2931 & 2.119 & 260.4 & 88.84 & 54.9 & 88.4 & 1 \\ 800 & 0.2739 & 2.152 & 278.6 & 101.7 & 59.2 & 100 & 1.01 \\ 850 & 0.2579 & 2.186 & 296.9 & 115.1 & 63.7 & 113 & 1.02 \end{array}$$

Then, extract the different columns as vectors:

$$TKelvin := M5^{\langle 0 \rangle} \quad Steam\_rho := M5^{\langle 1 \rangle} \quad Steam\_cp := M5^{\langle 2 \rangle} \quad Steam\_mu := M5^{\langle 3 \rangle}$$

$$Steam\_nu := M5^{\langle 4 \rangle} \quad Steam\_k := M5^{\langle 5 \rangle} \quad Steam\_alpha := M5^{\langle 6 \rangle} \quad Steam\_Pr := M5^{\langle 7 \rangle}$$

**And, now write the Mathcad Functions to get different properties (i.e. rho, cp, mu and k) of Steam as functions of Temp by linear interpolation in Mathcad:**

**T (K) , rho_steam (kg/m^3).:**

```
rho_steam(TKelvin, Steam_rho, T) := | return "T must be between 380 K and 850 K !!" if T < 380
                                    | return "T must be between 380 K and 850 K !!" if T > 850
                                    | rho ← linterp(TKelvin, Steam_rho, T) otherwise
```

Ex: rho_steam(TKelvin, Steam_rho, 498) = 0.442

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**T (K) , cp_steam (J/kg.K).:**

$$cp\_steam(TKelvin, Steam\_cp, T) := \begin{cases} \text{return "T must be between 380 K and 850 K !!"} & \text{if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!"} & \text{if } T > 850 \\ cp \leftarrow \text{linterp}(TKelvin, Steam\_cp, T) \cdot 10^{3} & \text{otherwise} \end{cases}$$

Ex: $cp\_steam(TKelvin, Steam\_cp, 498) = 1.985 \times 10^{3}$

---

**T (K) , mu_steam (N.s/m^2).:**

$$mu\_steam(TKelvin, Steam\_mu, T) := \begin{cases} \text{return "T must be between 380 K and 850 K !!"} & \text{if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!"} & \text{if } T > 850 \\ mu \leftarrow \text{linterp}(TKelvin, Steam\_mu, T) \cdot 10^{-7} & \text{otherwise} \end{cases}$$

Ex: $mu\_steam(TKelvin, Steam\_mu, 498) = 1.697 \times 10^{-5}$

---

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**T (K) , k_steam (W/m.K).:**

$$k\_steam(TKelvin, Steam\_k, T) := \begin{cases} \text{return "T must be between 380 K and 850 K !!"} & \text{if } T < 380 \\ \text{return "T must be between 380 K and 850 K !!"} & \text{if } T > 850 \\ k \leftarrow linterp(TKelvin, Steam\_k, T) \cdot 10^{-3} & \text{otherwise} \end{cases}$$

Ex: $k\_steam(TKelvin, Steam\_k, 498) = 0.0337$

---

Now, while solving problems on Boiling, we need to solve for Nucleate boiling flux, max. (or, Critical) heat flux for horizontal or cylindrical surfaces, min. heat flux, film boiling heat transfer coefficients for horizontal or cylindrical surfaces etc.

Since these equations are rather complicated, we shall write Mathcad Functions for them using the property Functions written above, so that it will be very convenient to solve problems, as illustrated below.

Now, let us solve the above problem.

It is stated again:

**Prob.3.1.1:** Water at a pressure of one atm. is boiled in a polished copper pan, 300 mm dia. If the surface temperature of the pan is 110 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. heat flux.

**Mathcad Solution:**

**Since ΔTe < 30 C, it is Nucleate boiling regime.**

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**Let us write a Function for Nucleate boiling heat flux: (Remember that it is valid for all geometries)**

**Mathcad Function to find q_nucleate for Water boiling at 1 atm:**

**Input:** Ts (C), Tsat (C), Csf --from Table for Surface-fluid combination

**Output:** q_nucleate (W/m^2)

$$\text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf}) :=$$

return "Use Film boiling correlations since (Ts - Tsat) > 30 C! " if $(T_s - T_{sat}) > 30$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_{sat} + 273.15)$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_{sat} + 273.15)$$

$$Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_{sat} + 273.15)$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$

$$n \leftarrow 1$$

$$g \leftarrow 9.81$$

$$A \leftarrow mu_L \cdot h_{fg}$$

$$B \leftarrow \left[\frac{g \cdot (rho_L - rho_V)}{sigma}\right]^{\frac{1}{2}}$$

$$C \leftarrow \left[\frac{cp_L \cdot (T_s - T_{sat})}{C_{sf} \cdot h_{fg} \cdot Pr_L^{\,n}}\right]^3$$

$$q_{nucleate} \leftarrow A \cdot B \cdot C$$

**And, for max. heat flux for a Flat surface we write the Mathcad Function as:**

**Mathcad Function to find q_max (or, crit. heat flux) for Water, for a flat surface:**

**Input:** Tsat (C)
**Output:** q_max (W/m^2)

$$\text{NucleateBoiling\_Water\_FlatSurface\_q\_max}(T_{sat}) :=$$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_{sat} + 273.15)$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$

$$g \leftarrow 9.81$$

$$A \leftarrow 0.149 \cdot h_{fg} \cdot rho_V$$

$$B \leftarrow \left[\frac{g \cdot sigma \cdot (rho_L - rho_V)}{rho_V^{\,2}}\right]^{\frac{1}{4}}$$

$$q_{max} \leftarrow A \cdot B$$

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**And, for Min. heat flux, the Mathcad Function is:**

**Mathcad Function to find q_min (or, min.. heat flux) for Water, for a horizl. surface:**

**Input:** Tsat (C)

**Output:** q_min (W/m^2)

$$\text{NucleateBoiling\_Water\_HorizlPlate\_q\_min}(T_{sat}) :=$$

$$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_{sat} + 273.15)}$$

$$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$$

$$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$$

$$sigma \leftarrow sigma\_f\_H2O(TempK, H2Osigma\_f, T_{sat} + 273.15)$$

$$g \leftarrow 9.81$$

$$A \leftarrow 0.09 \cdot rho_V \cdot h_{fg}$$

$$B \leftarrow sigma \cdot g \cdot (rho_L - rho_V)$$

$$C \leftarrow (rho_L + rho_V)^2$$

$$q_{min} \leftarrow A \cdot \left(\frac{B}{C}\right)^{\frac{1}{4}}$$

$$q_{min}$$

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Now, we shall use these Functions to solve the above problem:

**Data:**

$T_s := 110$ C..temp. of surface

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$d := 0.3$ m....dia of pan

$C_{sf} := 0.013$ ...for water - polished copper combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.257 \times 10^6$ J/kg

Since ΔT is 10 deg.C, it is reasonable to assume that correlation for nucleate boiling regime is applicable. Then:

**We have the Mathcad Function for q in nucleate boiling:**

Applying the same:

$q_{nucleate} := NucleateBoiling\_Water\_q\_nucleate(T_s, T_{sat}, C_{sf})$

i.e. $q_{nucleate} = 1.369 \times 10^5$ **W/m^2.....Ans.**

**Heat transfer coeff.:**

We have: $h := \frac{q_{nucleate}}{(T_s - T_{sat})}$ W/(m².C)

i.e. $h = 1.369 \times 10^4$ **W/(m².C)....Ans.**

**Evaporation rate:**

Total amount of heat supplied: $Q := q_{nucleate} \cdot \left(\frac{\pi \cdot d^2}{4}\right)$ W

i.e. $Q = 9.678 \times 10^3$ W

Therefore, evap. rate of water: $m := \frac{Q}{h_{fg}}$ kg/s

i.e. $m = 4.288 \times 10^{-3}$ kg/s

i.e. $m = 15.742$ **kg/h....Ans.**

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**(b) Max. heat flux:**

**We have, from from the Mathcad Function for Max. heat fkux, q_max:**

$q_{max} := \text{NucleateBoiling\_Water\_FlatSurface\_q\_max}(T_{sat})$ W/m$^2$.....

i.e. $q_{max} = 1.259 \times 10^6$ **W/m$^2$....Ans.**

Thus, actual heat flux (q_nucleate) is much smaller than the critical (max) heat flux.

**(c) Min. heat flux:**

**We have, from from the Mathcad Function for Min. heat flux, q_min.:**

$q_{min} := \text{NucleateBoiling\_Water\_HorizlPlate\_q\_min}(T_{sat})$ W/m$^2$.....

i.e. $q_{min} = 1.895 \times 10^4$ **W/m$^2$....Ans.**

**Thus, we see that having Mathcad Functions made these calculations very easy.**

==========

**Prob.3.1.2:** Water at a pressure of one atm. is boiled in a mechanically polished stainless steel pan, 30 cm dia. If the heater is of 1.8 kW rating, assuming that all the heat supplied is transferred to the pan, determine the temp of inner surface of the pan. What will be evaporation rate of water?

**Mathcad Solution:**

**Note:** In Nucleate boiling regime, max. temp difference, $\Delta T_e$ is about 30 deg. C.

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So, we will assume $\Delta T_e$ = 20 C and, for polished S.S. take the value of $C_{sf}$ = 0.013 from Table, and find $q_s$. Then, apply Solve Block of Mathcad to get correct value of $T_s$ such that Q = 1.8 kW:

**Data:**

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$d := 0.3$ m....dia of pan

---

$C_{sf} := 0.013$ ...for water - polished SS combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.257 \times 10^6$ J/kg

$Q_{heater} := 1.8 \cdot 10^3$ W.... by data

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Now, first find the heat flux, qs:

$$q_s := \frac{Q}{\left(\frac{\pi \cdot d^2}{4}\right)} \quad \text{i.e.} \quad q_s = 1.369 \times 10^5 \quad \text{W/m^2}$$

In Nucleate boiling regime, we have:

$q_s = \text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf})$ ...using the Function for nucleate boiling flux

Here, qs is known, and Ts is the unknown.
So, apply 'Solve Block' construct of Mathcad to find Ts:

**Start with the assumed value of Ts:**

$T_s := 120$ C..temp. of surface... assumed, will be found out later.

Given

$q_s = \text{NucleateBoiling\_Water\_q\_nucleate}(T_s, T_{sat}, C_{sf})$

$T_s := \text{Find}(T_s)$

$T_s = 110$ **C .... temp of inner surface of pan .... Ans.**

**Evaporation rate:**

Total amount of heat supplied: $Q := 1800$ W

Therefore, evap. rate of water: $m := \frac{Q}{h_{fg}}$ kg/s

i.e. $m = 7.975 \times 10^{-4}$ kg/s

i.e. $m = 2.871$ **kg/h....Ans.**

==========

**Prob.3.1.3:** A 65 cm long, 2 cm dia brass heater is used to boil water at 120 C. Surface temp of heater is not allowed to exceed 125 C. Determine the rate of steam production in the boiler in kg/h.

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**Mathcad Solution:**

**Note:** In Nucleate boiling regime, max. temp difference, ΔTe is about 30 deg. C.
Here, we have, ΔTe = 5 C (i.e. < 30 C); **So, it is nucleate boiling regime.**
And, for water-brass combination, take the value of $C_{sf}$ = 0.006 from Table, and find $q_s$.

**Data:**

$T_s := 125$ C.... surface temp of heater

$T_{sat} := 120$ C...sat. temp. of water.

$d := 0.02$ m....dia of heater

$C_{sf} := 0.006$ ...for water - brass combination

$h_{fg} := h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$ J/kg ... applying the Mathcad Function for h_fg

i.e. $h_{fg} = 2.202 \times 10^6$ J/kg

In Nucleate boiling regime, we have:

$q_s := NucleateBoiling\_Water\_q\_nucleate(T_s, T_{sat}, C_{sf})$ ...using the Function for nucleate boiling flux

Therefore,

$q_s = 2.951 \times 10^5$ **W/m^2.....Ans.**

and, Heat supplied, Q = A * qs:

i.e. $Q := (\pi \cdot 0.02 \cdot 0.65) \cdot q_s$

i.e. $Q = 1.205 \times 10^4$ W

Therefore, evaporation rate:

$$m := \frac{Q}{h_{fg}}$$

i.e. $m = 5.474 \times 10^{-3}$ kg/s

i.e. $m \cdot 3600 = 19.705$ **kg/h .... Ans.**

==========

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**Prob.3.1.4:** A 20 mm dia, 0.75 m long copper tube is used to boil saturated water at 1 atm. Find the tube surface temp if heat flux is limited to 75 % of critical heat flux.
(b) Also, plot the surface temp. as function of heat flux for $0.25 < (q_s / q_{max}) < 0.90$.

**Mathcad Solution:**

**Note:** In Nucleate boiling regime, max. temp difference, $\Delta T_e$ is about 30 deg. C.

Here, *we assume* that it is nucleate boiling regime.
And, for water-copper combination, take the value of $C_{sf} = 0.013$ from Table.

Here, we need $q_{max}$ for a horizontal cylinder.

**Remember that max. heat flux depend on geometry of surface.**

**Now, we shall write a Function for max. flux for a horizl. Cylinder:**

**Mathcad Function to find q_max (or, crit. heat flux) for Water boiling for a horizl cylinder:**

**Input:** Tsat (C), Radius, R(m)

**Output:** q_max (W/m^2)

```
NucleateBoiling_Water_HorizlCylinder_q_max(T_sat, R) :=
    rho_L ← 1 / vf_H2O(TempK, H2Ov_f, T_sat + 273.15)
    rho_V ← 1 / vg_H2O(TempK, H2Ov_g, T_sat + 273.15)
    mu_L ← mu_f_H2O(TempK, H2Omu_f, T_sat + 273.15)
    h_fg ← h_fg_H2O(TempK, H2Oh_fg, T_sat + 273.15)
    sigma ← sigma_f_H2O(TempK, H2Osigma_f, T_sat + 273.15)
    g ← 9.81
    q_max_F ← 0.131·h_fg·√rho_V·[sigma·g·(rho_L − rho_V)]^(1/4)
    R_prime ← R·[g·(rho_L − rho_V) / sigma]^(1/2)
    q_max ← q_max_F·0.894  if  R_prime > 3.47
    q_max ← q_max_F·(0.89 + 2.27·exp(−3.44·√R_prime))  if  0.15 < R_prime < 3.47
    q_max
```

Observe that much calculation effort is required to do this calculation.

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However, having a Mathcad Function to do this, makes it simple to solve not only this problem, but all other similar problems.

**Data:**

$T_s := 105$ C.... surface temp of heater. .... asssumed

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$R := 0.01$ m....radius of copper tube

$C_{sf} := 0.013$ ...for water - copper combination

**For critical (or, max.) heat flux,** we have, the Mathcad Function already written::

$q_{max} := NucleateBoiling\_Water\_HorizlCylinder\_q\_max(T_{sat}, R)$ ...using the Function for nucleate boiling flux

Therefore,

$q_{max} = 9.893 \times 10^5$ **W/m^2.....Ans.**

For Nucleate boiling, by data, $q_s$ is 0.75 times $q_{max}$:

$q_s := 0.75 \cdot q_{max}$ i.e. $q_s = 7.42 \times 10^5$ W/m^2....Nucleate boiling flux

Now, use the Mathcad Function for Nucleate boiling heat flux and apply the Solve block to find surface temp, Ts.

**Start with an assumed value of Ts:**

$T_s := 105$ C.... surface temp of heater. .... asssumed

Given

$q_s = NucleateBoiling\_Water\_q\_nucleate(T_s, T_{sat}, C_{sf})$

$T_s(q_s) := Find(T_s)$

$T_s(q_s) = 117.564$ **C..... Surface temp...Ans.**

**Note:** We have written $T_s$ as a function of $q_s$ so that it will be easier to calculate values of $T_s$ for different values of $q_s$ (and plot the graph), by using the same Solve block.

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**To plot Ts for various values of (qs/qmax):**

Use the solution of Solve Box obtained above, by entering $q_s$ as a vector.

Note the use of *'vectorize operator'* to get values of $T_s$ for various values of $q_{max}$:

Here, first define Fraction as a vector, from 0.25 to 0.9, as required by the problem.
And, then, immediately, $q_s$ is calculated as a vector:

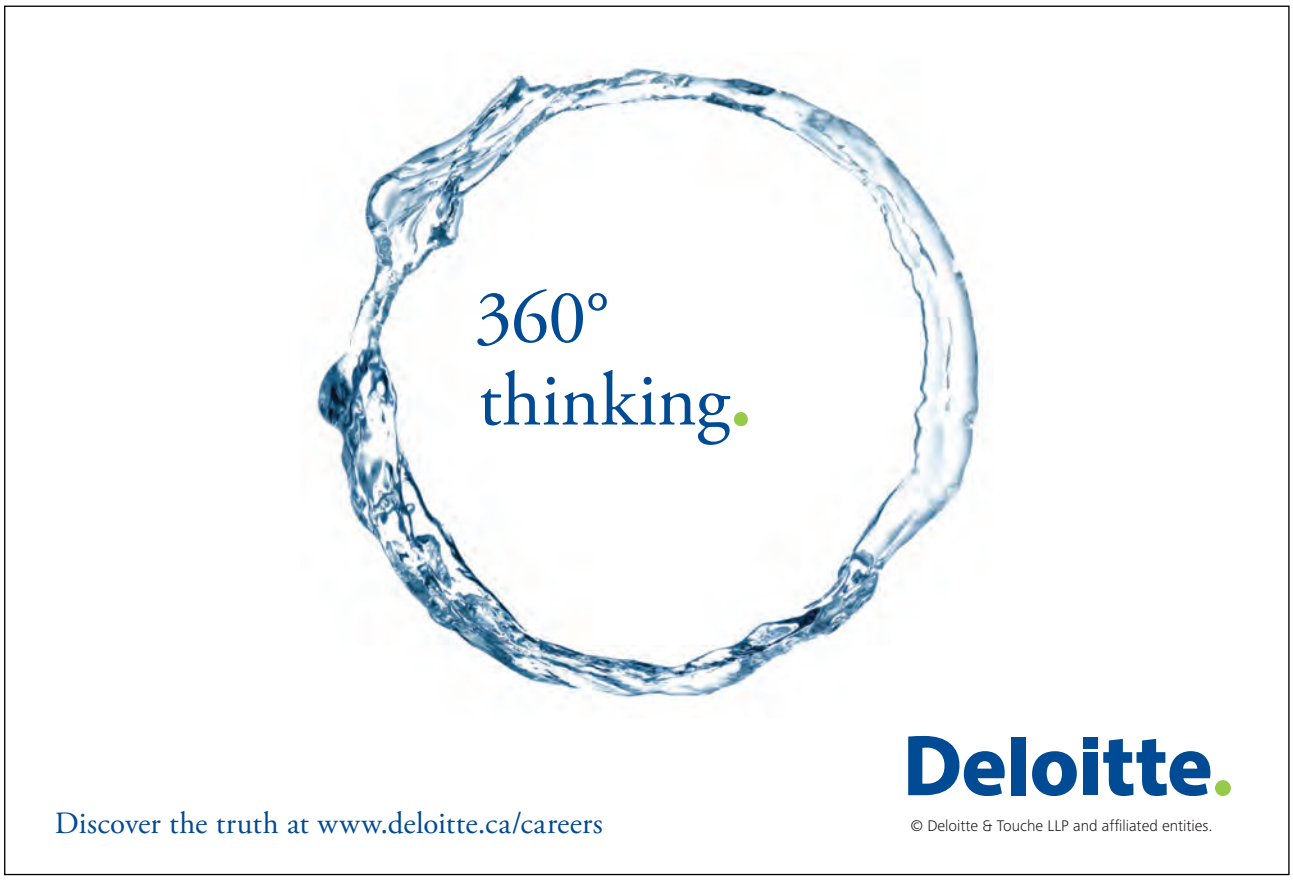
Fraction := (0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9) ...Fraction = qs/qmax

$q_s := q_{max} \cdot Fraction$ ....values of qs

Now, $T_s$ as a function of $q_s$ is easily calculated using the Solve block set up above. Note the use of vectorize operator (i.e. a horizontal arrow above $T_s$):

$\overrightarrow{T_s(q_{max} \cdot Fraction)} =$

| | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 112.179 | 112.942 | 113.624 | 114.244 | 114.814 | 115.344 | 115.839 | 116.305 | 116.746 |

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Get the results neatly in columns (useful for plotting):

**Results:**

Fraction of q_max | Values of qs (W) | Values of Ts (C)

$\text{Fraction}^T =$

| | 0 |
|---|---|
| 0 | 0.25 |
| 1 | 0.3 |
| 2 | 0.35 |
| 3 | 0.4 |
| 4 | 0.45 |
| 5 | 0.5 |
| 6 | 0.55 |
| 7 | 0.6 |
| 8 | 0.65 |
| 9 | 0.7 |
| 10 | 0.75 |
| 11 | 0.8 |
| 12 | 0.85 |
| 13 | 0.9 |

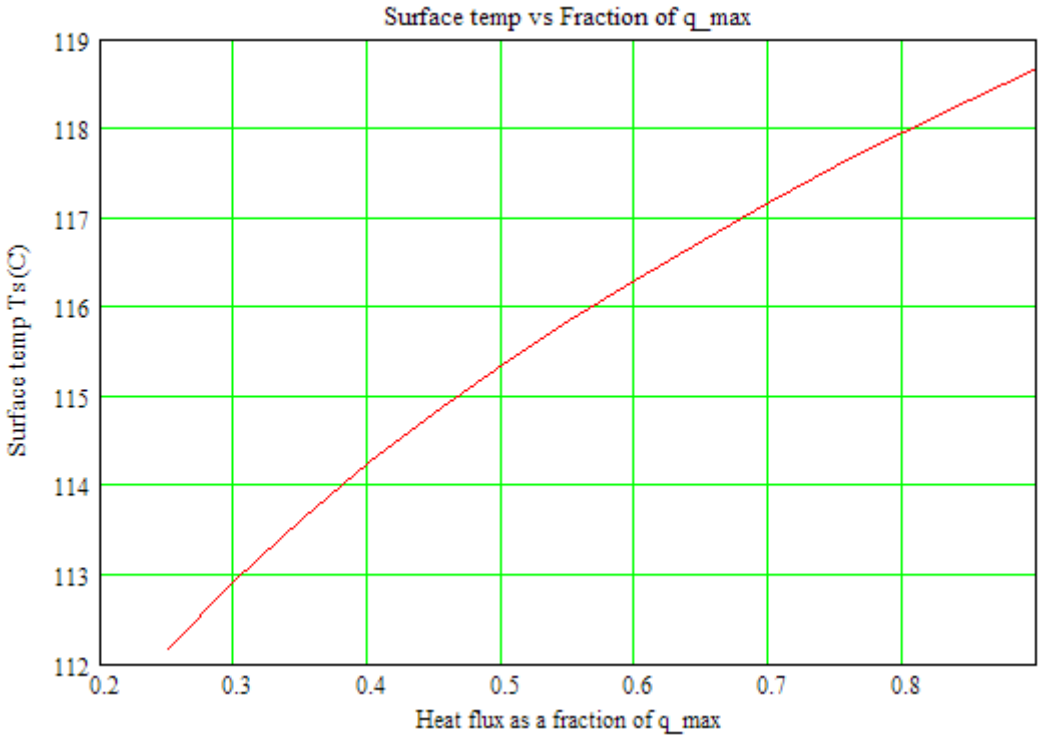
$q_s^T =$

| | 0 |
|---|---|
| 0 | $2.473 \cdot 10^5$ |
| 1 | $2.968 \cdot 10^5$ |
| 2 | $3.462 \cdot 10^5$ |
| 3 | $3.957 \cdot 10^5$ |
| 4 | $4.452 \cdot 10^5$ |
| 5 | $4.946 \cdot 10^5$ |
| 6 | $5.441 \cdot 10^5$ |
| 7 | $5.936 \cdot 10^5$ |
| 8 | $6.43 \cdot 10^5$ |
| 9 | $6.925 \cdot 10^5$ |
| 10 | $7.42 \cdot 10^5$ |
| 11 | $7.914 \cdot 10^5$ |
| 12 | $8.409 \cdot 10^5$ |
| 13 | $8.904 \cdot 10^5$ |

$\left(\overrightarrow{T_s(q_{max} \cdot \text{Fraction})}\right)^T =$

| | 0 |
|---|---|
| 0 | 112.179 |
| 1 | 112.942 |
| 2 | 113.624 |
| 3 | 114.244 |
| 4 | 114.814 |
| 5 | 115.344 |
| 6 | 115.839 |
| 7 | 116.305 |
| 8 | 116.746 |
| 9 | 117.165 |
| 10 | 117.564 |
| 11 | 117.946 |
| 12 | 118.313 |
| 13 | 118.665 |

**And, plot Ts against Fraction, in Mathcad:**

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**Prob.3.1.5:** A nickel wire, 1 mm dia. and 300 mm long, is submerged in a water bath open to atmosphere.

What is the value of current flowing through the wire that will cause burnout, if the applied voltage is 10 V?

**Mathcad Solution:**

**Data:**

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$R := 0.0005$ m....radius of wire

$L := 0.3$ m....length of wire

$V := 10$ V....applied voltage

This is the case of a horizontal cylinder.

So, let us use the Mathcad Function, already written, for max. (or, critical) heat flux for a horizontal cylinder.

$q_{max} := \text{NucleateBoiling\_Water\_HorizlCylinder\_q\_max}(T_{sat}, R)$

i.e. $q_{max} = 1.525 \times 10^6$ **W/m^2....This is the value of 'Burn-out' flux**

If V is the voltage, and, I the current through the wire, we have:

$$q_{max} = \frac{V \cdot I}{2 \cdot \pi \cdot R \cdot L}$$

i.e. $I := \frac{q_{max} \cdot 2 \cdot \pi \cdot R \cdot L}{V}$ A.....current through the wire

i.e. $I = 143.723$ **A.....current through the wire...Ans.**

==========

**Prob.3.1.6:** A horizontal, metal-clad heating element, 10 mm dia, and of surface emissivity 0.85, is submerged in a water bath. Surface temperature of the heating element is 300 C. If the water is at atmospheric pressure, calculate the power dissipation per unit length of the heater.

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**Mathcad Solution:**

Because of high surface temp, we know that $\Delta T_e$ will be > 30 C, and it will be **Film boiling regime**.

In Film boiling regime for a horizontal cylinder, we will write a Mathcad Function to calculate heat transfer coefficient, $h_{film}$:

**Mathcad Function to find h_film for Film boiling for Water boiling at 1 atm, for a horizl. cylinder:**
**Input:** Ts, Tsat (C), dia D (m)
**Output:** h_film (W/m^2.C)
**Note:** Take vapour properties at Tf, at 1 atm

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```
FilmBoiling_Water_HorizlCylinder_h_film(Ts, Tsat, D) :=
    return "Use Nucleate boiling correlations since (Ts - Tsat) < 30 C! " if (Ts − Tsat) < 30
    Tf ← (Ts + Tsat) / 2
    rhoL ← 1 / vf_H2O(TempK, H2Ov_f, Tsat + 273.15)
    rhoV ← rho_steam(TKelvin, Steam_rho, Tf + 273.15)
    hfg ← h_fg_H2O(TempK, H2Oh_fg, Tsat + 273.15)
    muV ← mu_steam(TKelvin, Steam_mu, Tf + 273.15)
    kV ← k_steam(TKelvin, Steam_k, Tf + 273.15)
    cpV ← cp_steam(TKelvin, Steam_cp, Tf + 273.15)
    sigma ← sigma_f_H2O(TempK, H2Osigma_f, Tsat + 273.15)
    hfg_prime ← hfg + 0.4·cpV·(Ts − Tsat)
    g ← 9.81
    C0 ← 0.62
    B ← g·rhoV·(rhoL − rhoV)·hfg_prime·kV^3
    C ← muV·(Ts − Tsat)·D
    hfilm ← C0·(B / C)^(1/4)
    hfilm
```

Now, let us solve the problem:

**Data:**

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$D := 0.01$ m....dia. of wire

$L := 1$ m....length of wire, assumed

$T_s := 300$ C....surface temp.

$\varepsilon := 0.85$ ...emissivity of surface

$\sigma := 5.67 \cdot 10^{-8}$ W/(m$^2$.K$^4$)...Stefan-Boltzmann const.

Since the excess temp. is (300 – 100) = 200 C, it is **film boiling region.**

We will use the Mathcad Function already written for Film boiling on a cylinder:

$h_{film} := FilmBoiling\_Water\_HorizlCylinder\_h\_film(T_s, T_{sat}, D)$

i.e. $h_{film} = 198.709$ **W/m^2.C ..... film boiling heat transfer coeff.**

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**Note:** In film boiling, since surface temp is generally high, we have to include the effect of radiation too:

**Radiative heat transfer coeff. is given by:**

$$h_{rad} := \frac{\sigma \cdot \varepsilon \cdot \left[ (T_s + 273)^4 - (T_{sat} + 273)^4 \right]}{(T_s - T_{sat})} \qquad W/(m^2.C).....$$

i.e. $h_{rad} = 21.313$ $W/(m^2.C)$

**Note:** Use absolute temperatures in eqn. for for radiative heat transfer

**Therefore, the 'total' heat transfer coeff. is given by:**

$$h := h_{film} + 0.75 \cdot h_{rad} \qquad ..W/m^2.C$$

i.e. $h = 214.693$ $W/(m^2.C)$

**Therefore, power dissipation per unit length of heater:**

$$Q := h \cdot (\pi \cdot D \cdot L) \cdot (T_s - T_{sat}) \qquad W/m$$

i.e. $Q = 1.349 \times 10^3$ **W/m....Ans.**

==========

**Prob.3.1.7:** A large, horizontal plate is kept immersed in a water bath boiling at 1 atm, 100 C. Surface temperature of the plate is 260 C. Calculate the heat transfer coeff. and the heat flux. Assume the emissivity of the surface as 0.9.

**Mathcad Solution:**

Because of high surface temp, we know that $\Delta T_e$ will be > 30 C, and it will be **Film boiling regime**.

**In Film boiling regime for a horizontal plate**, we will write a Mathcad Function to calculate heat transfer coefficient, $h_{film}$:

**Mathcad Function to find h_film for Film boiling for Water boiling, for a horizl. surface:**

**Input:** Ts, Tsat (C)

**Output:** h_film (W/m^2.C)

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**Note:** Take vapour properties at Tf, at 1 atm

$$\text{FilmBoiling\_Water\_HorizlPlate\_h\_film}(T_s, T_{sat}) :=$$

return "Use Nucleate boiling correlations since (Ts - Tsat) < 30 C! " if $(T_s - T_{sat}) < 30$

$T_f \leftarrow \frac{T_s + T_{sat}}{2}$

$\text{rho}_L \leftarrow \frac{1}{\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, T_{sat} + 273.15)}$

$\text{rho}_V \leftarrow \text{rho\_steam}(\text{TKelvin}, \text{Steam\_rho}, T_f + 273.15)$

$h_{fg} \leftarrow \text{h\_fg\_H2O}(\text{TempK}, \text{H2Oh\_fg}, T_{sat} + 273.15)$

$\text{mu}_V \leftarrow \text{mu\_steam}(\text{TKelvin}, \text{Steam\_mu}, T_f + 273.15)$

$k_V \leftarrow \text{k\_steam}(\text{TKelvin}, \text{Steam\_k}, T_f + 273.15)$

$\text{cp}_V \leftarrow \text{cp\_steam}(\text{TKelvin}, \text{Steam\_cp}, T_f + 273.15)$

$\text{sigma} \leftarrow \text{sigma\_f\_H2O}(\text{TempK}, \text{H2Osigma\_f}, T_{sat} + 273.15)$

$h_{fg\_prime} \leftarrow h_{fg} + 0.4 \cdot \text{cp}_V \cdot (T_s - T_{sat})$

$g \leftarrow 9.81$

$C_0 \leftarrow 0.59$

$B \leftarrow g \cdot \text{rho}_V \cdot (\text{rho}_L - \text{rho}_V) \cdot h_{fg\_prime} \cdot k_V^3$

$C \leftarrow \text{mu}_V \cdot (T_s - T_{sat}) \cdot 2 \cdot \pi \cdot \left[\frac{\text{sigma}}{g \cdot (\text{rho}_L - \text{rho}_V)}\right]^{\frac{1}{2}}$

$h_{film} \leftarrow C_0 \cdot \left(\frac{B}{C}\right)^{\frac{1}{4}}$

$h_{film}$

**Now, solve the above problem:**

**Data:**

$T_{sat} := 100$ C...sat. temp. of water at 1 atm.

$T_s := 260$ C....surface temp.

$\varepsilon := 0.9$ ...emissivity of surface

Since the excess temp. is (260 – 100) = 160 C, it is **film boiling region.**

We will use the Mathcad Function already written for heat transfer coeff in film boiling for a flat surface in water:

$h_{film} := \text{FilmBoiling\_Water\_HorizlPlate\_h\_film}(T_s, T_{sat})$

i.e. $h_{film} = 174.934$ **W/m^2.C ..... film boiling heat transfer coeff.**

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**And, Radiative heat transfer coeff.:**

$\sigma := 5.67 \cdot 10^{-8}$ W/(m$^2$.K$^4$)...Stefan-Boltzmann const.

$$h_{rad} := \frac{\sigma \cdot \varepsilon \cdot \left[ (T_s + 273)^4 - (T_{sat} + 273)^4 \right]}{(T_s - T_{sat})} \quad \text{W/(m}^2\text{.C)...}$$

i.e. $h_{rad} = 19.567$ W/(m$^2$.C)

**Note:** Use absolute temperatures in eqn. for for radiative heat transfer

**Therefore, the 'total' heat transfer coeff. is given by:**

$$h := h_{film} + 0.75 \cdot h_{rad} \quad \text{....(11.17)}$$

i.e. $h = 189.609$ **W/(m$^2$.C).....Ans.**

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**And, the heat flux:**

$$q := h \cdot (T_s - T_{sat}) \quad W/m^2$$

i.e. $q = 3.034 \times 10^4$ **W/m²...Ans.**

==========

**EES Procedures / Functions for Boiling heat transfer calculations:**

EES has a great advantage that it has built-in functions for properties of a large number of fluids including Water/steam.

So, it is very easy to write Functions or Procedures for various boiling heat transfer calculations.

**First, let us write Functions for Nucleate boiling heat flux, critical (or Max.) heat flux for a horizontal surface, for a horizontal cylinder, and for a Sphere:**

```
$UnitSystem SI Pa C J

"EES Procedures for Boiling calculations:"

"Nucleate Boiling of Water – heat flux: valid for any geometry:"

FUNCTION NucleateBoiling_flux_water(T_sat, T_s, C_sf)

"Nucleate boiling of water – heat flux (W/m^2):"

"Note: C_sf is the surface-fluid combination factor-from Handbook"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
k_l:=Conductivity(Steam_IAPWS,T=T_sat, x = 0) "[W/m-C]"
mu_l:=Viscosity(Steam_IAPWS,T=T_sat,x=0) "[kg/m-s]"
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
Pr_l:=Prandtl(Steam_IAPWS,T=T_sat,x=0)
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"
cp_l:=SpecHeat(Steam_IAPWS,T=T_sat,x=0) "[J/kg-C]"
```

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NucleateBoiling_flux_water:= mu_l * h_fg * (g * (rho_l – rho_v)/sigma)^(1/2) * (cp_l * (T_s – T_sat)/(C_sf * h_fg * Pr_l))^3

END

“ ”

“Nucleate Boiling of Water – Critical heat flux: depends on geometry:”

“For large, horizontal surface:”

FUNCTION Water_horizl_surface_q_max(T_sat)

“Nucleate boiling of water – critical heat flux (W/m^2):”

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) “[kg/m^3]”
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) “[kg/m^3]”
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) “[J/kg]”
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) “[J/kg]”
h_fg:= h_g – h_f “[J/kg]”
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) “N/m”
{q_max:= 0.149 * h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)}

Water_horizl_surface_q_max=0.149 * h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)

END

“ ”

“Nucleate Boiling of Water – Critical heat flux: depends on geometry:”

“For horizontal cylinder:”

FUNCTION Water_horizl_cylinder_q_max (T_sat,R)

“Nucleate boiling of water – critical heat flux (W/m^2):”

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) “[kg/m^3]”
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) “[kg/m^3]”

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```
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"

R_star:=R*(g*(rho_l-rho_v)/sigma)^0.5
If R_star > 1.2 Then
    C_cr:=0.12
    Water_horizl_cylinder_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf
If (R_star < 1.2) And (R_star > 0.15) Then
    C_cr:=0.12 * R_star^(-0.25)
    Water_horizl_cylinder_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf

END
```

“ ---------- ”

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"Nucleate Boiling of Water – Critical heat flux: depends on geometry:"

"For a Sphere:"

```
FUNCTION Water_sphere_q_max (T_sat,R)

"Nucleate boiling of water – critical heat flux (W/m^2):"

g:= 9.81[m/s^2]
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"
rho_v:=Density(Steam_IAPWS,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"

R_star:=R * (g * (rho_l – rho_v) / sigma)^0.5
If R_star > 4.26 Then
    C_cr:=0.11
    Water_sphere_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf
If (R_star < 4.26) And (R_star > 0.15) Then
    C_cr:=0.227 * R_star^(-0.5)
    Water_sphere_q_max:=C_cr*h_fg * rho_v * (sigma * g * (rho_l – rho_v)/ rho_v^2)^(1/4)
EndIf

END
```

" ---------- "

**Now, let us write Functions in EES for Film boiling heat transfer coeff./heat flux:**

"Film Boiling of Water – heat flux: depends on geometry:"

"For horizontal cylinder:"

```
FUNCTION Water_horizl_cylinder_q_film (T_sat, T_s, D)
```

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"Film boiling of water – heat flux (W/m^2):"

P_sat:=P_sat(Steam_IAPWS,T=T_sat) "[Pa]"
g:= 9.81[m/s^2]
T_f:=(T_s + T_sat) / 2 "[C]….film temp"
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"

"Properties of vap. at film temp T_f, and at a pressure of P_sat corresponding to T_sat:"

rho_v:=Density(Steam_IAPWS,T=T_f, P=P_sat) "[kg/m^3]"
cp_v:=Cp(Steam_IAPWS,T=T_f,P=P_sat) "[J/kg-C]"
mu_v:=Viscosity(Steam_IAPWS,T=T_f,P=P_sat) "[kg/m-s]"
k_v:=Conductivity(Steam_IAPWS,T=T_f,P=P_sat) "[W/m-C]"

"To determine h_fg:"

h_vap:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_liq:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_vap – h_liq "[J/kg]"

sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"
AA:= g * k_v^3 * rho_v * (rho_l – rho_v)
BB:= h_fg + 0.4 * cp_v * (T_s – T_sat)
CC: = mu_v * D * (T_s – T_sat)

Water_horizl_cylinder_q_film:=0.62 * (AA * BB / CC)^(1/4) * (T_s – T_sat)

END

" "

"Film Boiling of Water – heat flux: depends on geometry:"

"For horizontal surface:"

PROCEDURE Water_horizl_surface_q_film (T_sat, T_s: h_film, q_film)

"Film boiling of water –

Input: T-sat, T_s (deg.C)

Output: h_film (W/m^2-C) and heat flux (W/m^2):"

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P_sat:=P_sat(Steam_IAPWS,T=T_sat) "[Pa]"
g:= 9.81[m/s^2]
T_f:=(T_s + T_sat) / 2 "[C]….film temp"
rho_l:=Density(Steam_IAPWS,T=T_sat, x=0) "[kg/m^3]"

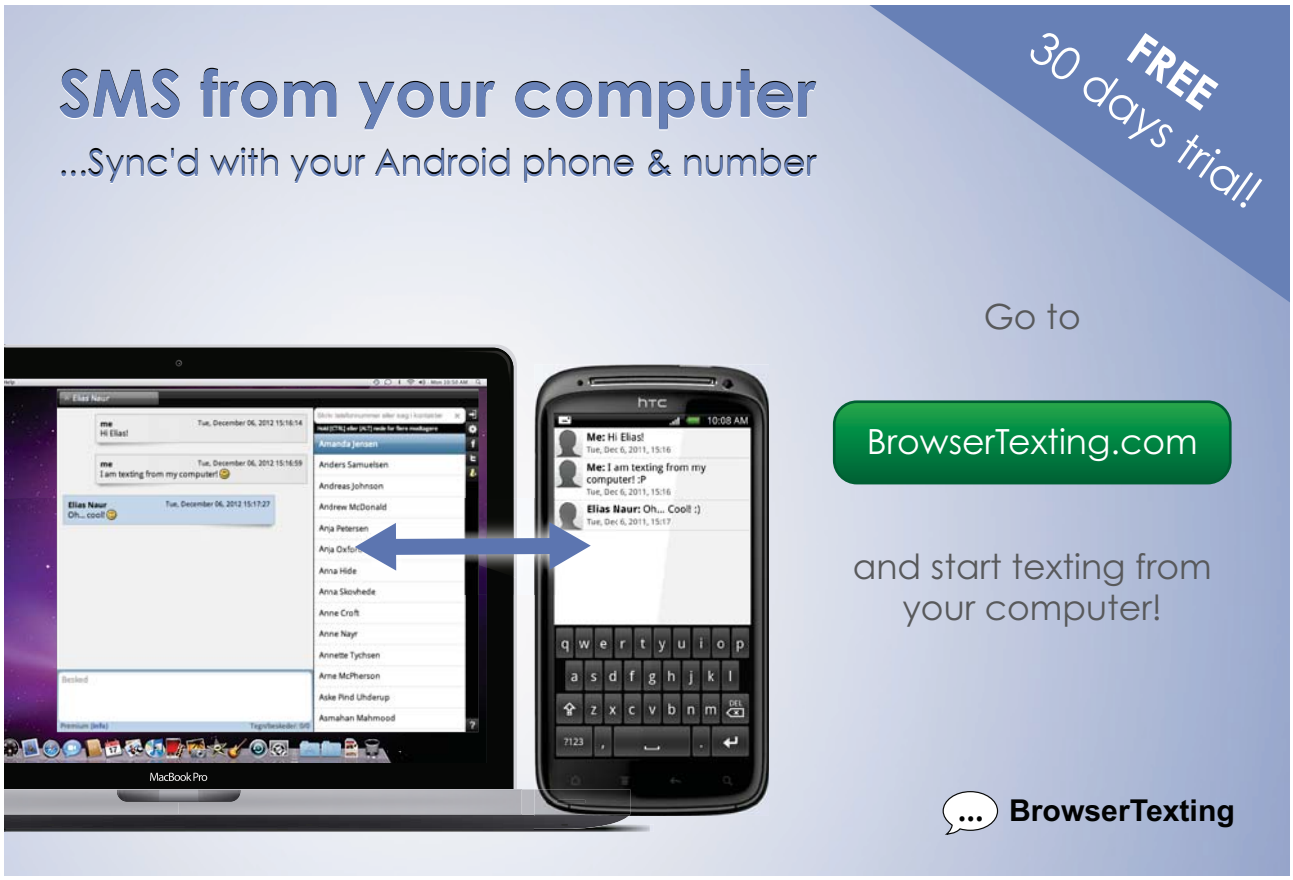
"Properties of vap. at film temp T_f, and at a pressure of P_sat corresponding to T_sat:"

rho_v:=Density(Steam_IAPWS,T=T_f, P=P_sat) "[kg/m^3]"
cp_v:=Cp(Steam_IAPWS,T=T_f,P=P_sat) "[J/kg-C]"
mu_v:=Viscosity(Steam_IAPWS,T=T_f,P=P_sat) "[kg/m-s]"
k_v:=Conductivity(Steam_IAPWS,T=T_f,P=P_sat) "[W/m-C]"

"To determine h_fg:"

h_vap:=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"
h_liq:=Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"
h_fg:= h_vap – h_liq "[J/kg]"

sigma:=SurfaceTension(Steam_IAPWS,T=T_sat) "N/m"

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C_0:=0.59 "..for horizl surface:"

Lambda:= 2 * pi * (sigma / (g * (rho_l – rho_v)))^(1/2)

AA:= g * rho_v * (rho_l – rho_v)*k_v^3
BB:= h_fg + 0.4 * cp_v * (T_s – T_sat)
CC: = mu_v * Lambda * (T_s – T_sat)

h_film:=C_0 * ( AA * BB / CC)^(1/4) "[W/m^2-C]"

q_film:=h_film * (T_s – T_sat) "[W/m^2]"

END

" "

**Now, let us solve some problems in EES using these Functions/Procedures:**

**Prob.3.1.8:** Water at a pressure of one atm. is boiled in a polished copper pan, 150 mm dia. If the surface temperature of the pan is 115 C, (a) calculate the boiling heat flux and the heat transfer coefficient. What is the evaporation rate of water? (b) compare the nucleate boiling flux with the max. (or critical) heat flux.

(c) what pan temp is required to achieve the critical heat flux?

**EES Solution:**

**"Data:"**

T_s = 115 [C]

T_sat = 100 [C]

D = 0.15 [m]

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)

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h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

Q = q_s * (pi * D^2 /4) "[W] …. Total heat tr to pan"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) * 3600 "[kg/s]"

"Max. or critical heat flux:"

"Using the EES Function written above:"

q_max = Water_horizl_surface_q_max(T_sat ) "[W/m^2]"

"What is the pan temp when critical heat flux is reached?"

"Put q_s = q_max in the relation for Nucleate boiling flux:"

q_max = NucleateBoiling_flux_water(T_sat, T_max, C_sf) "…determines T_max when q_max is reached"

**Results:**

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $C_{sf}$ = 0.013 | D = 0.15 [m] | $h_{fg}$ = 2.256E+06 [J/kg] |
| $h_{liq}$ = 419169 [J/kg] | $h_{nucleate}$ = 31693 [W/m$^2$-C] | $h_{vap}$ = 2.676E+06 [J/kg] |
| $m_{evap}$ = 13.4 [kg/h] | Q = 8401 [W] | $q_{max}$ = 1.261E+06 [W/m$^2$] |
| $q_s$ = 4.75391E+05 [W/m$^2$] | $T_{max}$ = 120.8 [C] | $T_s$ = 115 [C] |
| $T_{sat}$ = 100 [C] | | |

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Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

**Local variables in Function NucleateBoiling_flux_water (19 calls, 0.03 sec)**

| | |
|---|---|
| $cp_l$ =4216 [J/kg-C] | $C_{sf}$ =0.013 |
| g=9.81 [m/s$^2$] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $k_l$ =0.6791 [W/m-C] | $\mu_l$ =0.0002817 [kg/m-s] |
| $NucleateBoiling_{flux,water}$=1.261E+06 [W/m$^2$] | $Pr_f$=1.749 |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $\sigma$ =0.05891 [N/m] | $T_s$=120.8 [C] |
| $T_{sat}$ =100 [C] | |

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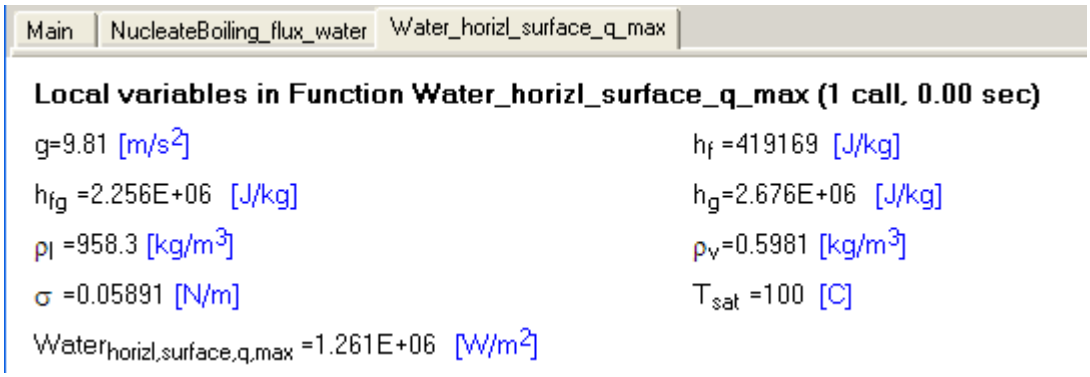


**Thus:**

**q_nucleate = q_s = 4.75391E05 W/m^2 …. Ans.**

**h_nucleate = 31693 W/m^2-C … Ans.**

**m_evap = 13.4 kg/h …. Ans.**

**q_max = 1.261E06 W/m^2 ….Ans.**

**T_max = 120.8 C … Ans.**

==========

**Prob.3.1.9:** Water at atmospheric pressure is to be boiled in a polished copper pan. Dia of the pan is 350 mm and is kept at 115 C. Assume C_sf = 0.013. Assuming Rosenhow relation holds good for Nucleate boiling conditions, calculate:

i) Power of the burner, Q
ii) Rate of evaporation of water, and
iii) Critical heat flux for these conditions.

**EES Solution:**

**"Data:"**

T_s = 115 [C]

T_sat = 100 [C]

D = 0.35 [m]

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

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q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)

h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

"Power of the burner:"

Q = q_s * (pi * D^2 /4) "[W] …. Power of the burner"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) "[kg/s]"

"Max. or critical heat flux:"

"Using the EES Function written above:"

q_max = Water_horizl_surface_q_max(T_sat ) "[W/m^2]"

**Results:**

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $C_{sf}$ = 0.013 | D = 0.35 [m] | $h_{fg}$ = 2.256E+06 [J/kg] |
| $h_{liq}$ = 419169 [J/kg] | $h_{nucleate}$ = 31693 [W/m$^2$-C] | $h_{vap}$ = 2.676E+06 [J/kg] |
| $m_{evap}$ = 0.02027 [kg/s] | Q = 45738 [W] | $q_{max}$ = 1.261E+06 [W/m$^2$] |
| $q_s$ = 4.75391E+05 [W/m$^2$] | $T_s$ = 115 [C] | $T_{sat}$ = 100 [C] |

Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

**Local variables in Function NucleateBoiling_flux_water (1 call, 0.00 sec)**

| | |
|---|---|
| $cp_l$ =4216 [J/kg-C] | $C_{sf}$ =0.013 |
| g=9.81 [m/s$^2$] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $k_l$ =0.6791 [W/m-C] | $\mu_l$ =0.0002817 [kg/m-s] |
| $NucleateBoiling_{flux,water}$=475391 [W/m$^2$] | Pr=1.749 |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $\sigma$ =0.05891 [N/m] | $T_s$=115 [C] |
| $T_{sat}$ =100 [C] | |

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Main | NucleateBoiling_flux_water | Water_horizl_surface_q_max

**Local variables in Function Water_horizl_surface_q_max (1 call, 0.00 sec)**

| | |
|---|---|
| $g$=9.81 [m/s$^2$] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $\sigma$ =0.05891 [N/m] | $T_{sat}$ =100 [C] |

$Water_{horizl,surface,q,max}$ =1.261E+06 [W/m$^2$]

**Thus:**

**q_nucleate = q_s = 4.75391E05 W/m^2 …. Ans.**

**Q = 45738 W … Ans.**

**m_evap = 0.02027 kg/s …. Ans.**

**q_max = 1.261E06 W/m^2 ….Ans.**

==========

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"**Prob.3.1.10:** Sat. water at T_sat = 100 C is boiled inside a copper pan having a heating surface area 0f 0.05 m^2, which is maintained at a uniform surface temp of T_s = 110 C. Calculate:

i) the surface heat flux, q
ii) rate of evaporation of water. [VTU – Dec. 2009/Jan. 2010]"

**"Data:"**

T_s = 110 [C]

T_sat = 100 [C]

A_s = 0.05 [m^2]

A_s = pi * D^2 / 4 "….finds dia D [m]"

C_sf = 0.013 "…for water – polished copper combination"

"Let us use the EES Functions/Procedures written above:"

"Nucleate boiling heat flux:"

q_s = NucleateBoiling_flux_water(T_sat, T_s, C_sf)

h_nucleate = q_s/(T_s – T_sat) "[W/m^2-C]"

"Power of the burner:"

Q = q_s * A_s "[W] …. Power of the burner"

h_liq = Enthalpy(Steam_IAPWS,T=T_sat,x=0) "[J/kg]"

h_vap=Enthalpy(Steam_IAPWS,T=T_sat,x=1) "[J/kg]"

h_fg = h_vap – h_liq "[J/kg]"

"Evaporation rate:"

m_evap = (Q / h_fg) "[kg/s]"

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**Results:**

Main | NucleateBoiling_flux_water

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $A_s$ = 0.05 [$m^2$] | $C_{sf}$ = 0.013 | D = 0.2523 [m] |
| $h_{fg}$ = 2.256E+06 [J/kg] | $h_{liq}$ = 419169 [J/kg] | $h_{nucleate}$ = 14086 [$W/m^2$-C] |
| $h_{vap}$ = 2.676E+06 [J/kg] | $m_{evap}$ = 0.003121 [kg/s] | Q = 7043 [W] |
| $q_s$ = 1.40857E+05 [$W/m^2$] | $T_s$ = 110 [C] | $T_{sat}$ = 100 [C] |

Main | NucleateBoiling_flux_water

**Local variables in Function NucleateBoiling_flux_water (1 call, 0.00 sec)**

| | |
|---|---|
| $cp_l$ =4216 [J/kg-C] | $C_{sf}$ =0.013 |
| g=9.81 [$m/s^2$] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $k_l$ =0.6791 [W/m-C] | $\mu_l$ =0.0002817 [kg/m-s] |
| $NucleateBoiling_{flux,water}$=140857 [$W/m^2$] | $Pr_f$=1.749 |
| $\rho_l$ =958.3 [$kg/m^3$] | $\rho_v$=0.5981 [$kg/m^3$] |
| $\sigma$ =0.05891 [N/m] | $T_s$=110 [C] |
| $T_{sat}$ =100 [C] | |

**Thus:**

**q_nucleate = q_s = 1.40857E05 W/m^2 …. Ans.**

**Q = 7043 W … Ans.**

**m_evap = 0.003121 kg/s …. Ans.**

==========

"**Prob.3.1.11:** A nickel wire 1 mm dia and 400 mm long, is submerged in a water bath at 1 atm pressure. Calculate the current carried when burn-out occurs, if the applied voltage is 10 V."

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**EES Solution:**

**"Data:"**

T_sat = 100 [C]

D = 0.001[m]

R = D/2 "[m]….radius of wire"

L = 0.4 [m]

V = 10 [V]

"Use the EES Function for q_max for a horizl cylinder, written above:"

q_max = Water_horizl_cylinder_q_max (T_sat,R) "[W/m^2]….burn out flux"

"Equate q_max to the surface heat flux at burn out:"

q_max = (V * I) / (pi * D * L) " finds the current, I [amp]"

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**Results:**

Main | Water_horizl_cylinder_q_max

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $D = 0.001$ [m] | $I = 190.9$ [A] | $L = 0.4$ [m] |
| $q_{max} = 1.519E+06$ [W/m$^2$] | $R = 0.0005$ [m] | $T_{sat} = 100$ [C] |
| $V = 10$ [V] | | |

Main | Water_horizl_cylinder_q_max

**Local variables in Function Water_horizl_cylinder_q_max (1 call, 0.00 sec)**

| | |
|---|---|
| $C_{cr} = 0.1795$ | $g = 9.81$ [m/s$^2$] |
| $h_f = 419169$ [J/kg] | $h_{fg} = 2.256E+06$ [J/kg] |
| $h_g = 2.676E+06$ [J/kg] | $R = 0.0005$ [m] |
| $\rho_l = 958.3$ [kg/m$^3$] | $\rho_v = 0.5981$ [kg/m$^3$] |
| $R_{star} = 0.1997$ | $\sigma = 0.05891$ [N/m] |
| $T_{sat} = 100$ [C] | $Water_{horizl,cylinder,q,max} = 1.519E+06$ [W/m$^2$] |

**Thus:**

**Burn–out flux = q_max = 1.519 W/m^2 …. Ans.**

**Current at burn-out = 190.9 A …. Ans.**

==========

"**Prob.3.1.12:** Water is boiled at a rate of 25 kg/h in a polished copper pan, 280 mm in dia. at atmospheric pressure. Assuming nucleate boiling conditions, determine the temp of bottom surface of the pan."

**EES Solution:**

**"Data:"**

T_sat = 100 [C]

D = 0.28[m]

C_sf = 0.013 "..for polished copper – Water combination"

h_fg = 2.256E06 [J/kg] "…heat of vapourization of water at 1 atm."

Q = 25 * 2.256E06 / 3600 "[W]… total heat supplied to boil 25 kg/h of water"

q_s = Q / (pi * D^2 / 4) "[W/m^2]…..heat flux"

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"Use the EES Function for q_s , nucleate boiling flux, written above:"

q_s= NucleateBoiling_flux_water(T_sat, T_s, C_sf) "[W/m^2]….nucleate boiling flux"

"In the above, T_s is the only un-known; so, it is calculated."

**Results:**

Main | NucleateBoiling_flux_water

**Unit Settings: SI C Pa J mass deg**

$C_{sf}$ = 0.013 | D = 0.28 [m] | $h_{fg}$ = 2.256E+06 [J/kg]

Q = 15667 [W] | $q_s$ = 2.54431E+05 [W/m$^2$] | $T_s$ = 112.2 [C]

$T_{sat}$ = 100 [C]

Main | NucleateBoiling_flux_water

**Local variables in Function NucleateBoiling_flux_water (19 calls, 0.02 sec)**

| | |
|---|---|
| $cp_l$ =4216 [J/kg-C] | $C_{sf}$ =0.013 |
| g=9.81 [m/s$^2$] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $k_l$ =0.6791 [W/m-C] | $\mu_l$ =0.0002817 [kg/m-s] |
| $NucleateBoiling_{flux,water}$=254431 [W/m$^2$] | $Pr_f$=1.749 |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $\sigma$ =0.05891 [N/m] | $T_s$=112.2 [C] |
| $T_{sat}$ =100 [C] | |

**Thus:**

**Surface temp. T_s = 112.2 C …. Ans.**

==========

"**Prob.3.1.13:** A metal clad heating element of 10 mm dia and of emissivity 0.9 is submerged in a water bath horizontally. If the surface temp is 300 C, calculate the power dissipation per unit length of the heater. Water is at atm. pressure."

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**EES Solution:**

**"Data:"**

T_s = 300 [C]

T_sat = 100 [C]

D = 0.01[m]

epsilon = 0.9

sigma = 5.67E-08 [W/m^2-K^4] "…Stefan-Boltzmann const."

"Use the EES Function for q_film , film boiling flux, written above, for a horizl cylinder:"

q_film= Water_horizl_cylinder_q_film (T_sat, T_s, D) "[W/m^2]….film boiling flux"

"Therefore:"

h_film = q_film / (T_s – T_sat) "[W/m^2-C]…. conv. heat transfer coeff."

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h_rad = sigma * epsilon * ((T_s + 273)^4 – (T_sat + 273)^4) / (T_s – T_sat) "[W/m^2-C]…radn. heat tr. coeff."

"Total h:"

h_tot = h_film + 0.75 * h_rad "[W/m^2-C]…total heat tr. coeff."

"Therefore:

Power dissip. per unit length of heater:"

Q = h_tot * (pi * D * 1)* (T_s – T_sat) "[W/m]"

**Results:**

Main | Water_horizl_cylinder_q_film

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $D = 0.01$ [m] | $\varepsilon = 0.9$ | $h_{film} = 205.5$ [W/m$^2$-C] |
| $h_{rad} = 22.57$ [W/m$^2$-C] | $h_{tot} = 222.5$ [W/m$^2$-C] | $Q = 1398$ [W/m] |
| $q_{film} = 41108$ [W/m$^2$] | $\sigma = 5.670E\text{-}08$ [W/m$^2$-K$^4$] | $T_s = 300$ [C] |
| $T_{sat} = 100$ [C] | | |

Main | Water_horizl_cylinder_q_film

**Local variables in Function Water_horizl_cylinder_q_film (1 call, 0.02 sec)**

| | |
|---|---|
| AA =0.1619 | BB =2.415E+06 |
| CC =0.00003235 | $cp_v$=1976 [J/kg-C] |
| D =0.01 [m] | g=9.81 [m/s$^2$] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_{liq}$ =419169 [J/kg] |
| $h_{vap}$ =2.676E+06 [J/kg] | $k_v$=0.03329 [W/m-C] |
| $\mu_v$=0.00001618 [kg/m-s] | $P_{sat}$ =101418 [Pa] |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.4669 [kg/m$^3$] |
| $\sigma$ =0.05891 [N/m] | $T_f$=200 [C] |
| $T_s$=300 [C] | $T_{sat}$ =100 [C] |
| $Water_{horizl,cylinder,q,film}$=41108 [W/m$^2$] | |

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**Thus:**

**Power dissip. per unit length of heater = Q = 1398 W/m …. Ans.**

==========

"**Prob.3.1.14:** An electrical conductor, 2 mm dia and of emissivity 0.5 is submerged in a water bath horizontally. If the surface temp is 555 C, calculate the power dissipation per unit length of the heater. Water is at atm. pressure.

(b) Also, plot the Power dissipation per unit length as a function of surface temp (T_s varying from 250 C to 650 C) for conductor diameters of: 1.5 mm, 2 mm and 2.5 mm."

**EES Solution:**

**"Data:"**

T_s = 555 [C]

T_sat = 100 [C]

D = 0.002[m]

epsilon = 0.5

sigma = 5.67E-08 [W/m^2-K^4] "…Stefan-Boltzmann const."

"Use the EES Function for q_film , film boiling flux, written above, for a horizl cylinder:"

q_film= Water_horizl_cylinder_q_film (T_sat, T_s, D) "[W/m^2]….film boiling flux"

"Therefore:"

h_film = q_film / (T_s – T_sat) "[W/m^2-C]…. conv. heat transfer coeff."

h_rad = sigma * epsilon * ((T_s + 273)^4 – (T_sat + 273)^4) / (T_s – T_sat) "[W/m^2-C]…radn. heat tr. coeff."

"Total h:"

h_tot = h_film + 0.75 * h_rad "[W/m^2-C]…total heat tr. coeff."

"Therefore:

Power dissip. per unit length of heater:"

Q = h_tot * (pi * D * 1)* (T_s – T_sat) "[W/m]"

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**Results:**

Main | Water_horizl_cylinder_q_film

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| D = 0.002 [m] | ε = 0.5 | $h_{film}$ = 287.8 [W/m$^2$-C] |
| $h_{rad}$ = 28.08 [W/m$^2$-C] | $h_{tot}$ = 308.9 [W/m$^2$-C] | Q = 883.1 [W/m] |
| $q_{film}$ = 130961 [W/m$^2$] | σ = 5.670E-08 [W/m$^2$-K$^4$] | $T_s$ = 555 [C] |
| $T_{sat}$ = 100 [C] | | |

Main | Water_horizl_cylinder_q_film

**Local variables in Function Water_horizl_cylinder_q_film (1 call, 0.00 sec)**

| | |
|---|---|
| AA =0.3451 | BB =2.625E+06 |
| CC =0.0000195 | $cp_v$=2027 [J/kg-C] |
| D =0.002 [m] | g=9.81 [m/s$^2$] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_{liq}$ =419169 [J/kg] |
| $h_{vap}$ =2.676E+06 [J/kg] | $k_v$=0.04644 [W/m-C] |
| $\mu_v$=0.00002143 [kg/m-s] | $P_{sat}$ =101418 [Pa] |
| $\rho_l$ =958.3 [kg/m$^3$] | $\rho_v$=0.3666 [kg/m$^3$] |
| σ =0.05891 [N/m] | $T_f$=327.5 [C] |
| $T_s$=555 [C] | $T_{sat}$ =100 [C] |
| $Water_{horizl,cylinder,q,film}$=130961 [W/m$^2$] | |

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**Now, to plot Q vs T_s: Produce 3 parametric Tables, each for D = 0.0015 m, 0.002 m, and 0.0025 m:**

**For D = 0.0015 m:**

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

| 1..9 | 1 $T_s$ [C] | 2 $h_{film}$ [W/m2-C] | 3 $h_{rad}$ [W/m2-C] | 4 Q [W/m] |
|---|---|---|---|---|
| Run 1 | 250 | 345.3 | 10.48 | 249.6 |
| Run 2 | 300 | 330.3 | 12.54 | 320.1 |
| Run 3 | 350 | 321.2 | 14.89 | 391.5 |
| Run 4 | 400 | 315.5 | 17.56 | 464.7 |
| Run 5 | 450 | 312.1 | 20.56 | 540.2 |
| Run 6 | 500 | 310.2 | 23.93 | 618.5 |
| Run 7 | 550 | 309.3 | 27.68 | 700 |
| Run 8 | 600 | 309.3 | 31.84 | 784.9 |
| Run 9 | 650 | 309.8 | 36.41 | 873.7 |

**For D = 0.002 m:**

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

| 1..9 | 1 $T_s$ [C] | 2 $h_{film}$ [W/m2-C] | 3 $h_{rad}$ [W/m2-C] | 4 Q [W/m] |
|---|---|---|---|---|
| Run 1 | 250 | 321.4 | 10.48 | 310.3 |
| Run 2 | 300 | 307.4 | 12.54 | 398.1 |
| Run 3 | 350 | 298.9 | 14.89 | 487 |
| Run 4 | 400 | 293.6 | 17.56 | 578.3 |
| Run 5 | 450 | 290.4 | 20.56 | 672.6 |
| Run 6 | 500 | 288.7 | 23.93 | 770.6 |
| Run 7 | 550 | 287.9 | 27.68 | 872.6 |
| Run 8 | 600 | 287.8 | 31.84 | 979.2 |
| Run 9 | 650 | 288.3 | 36.41 | 1091 |

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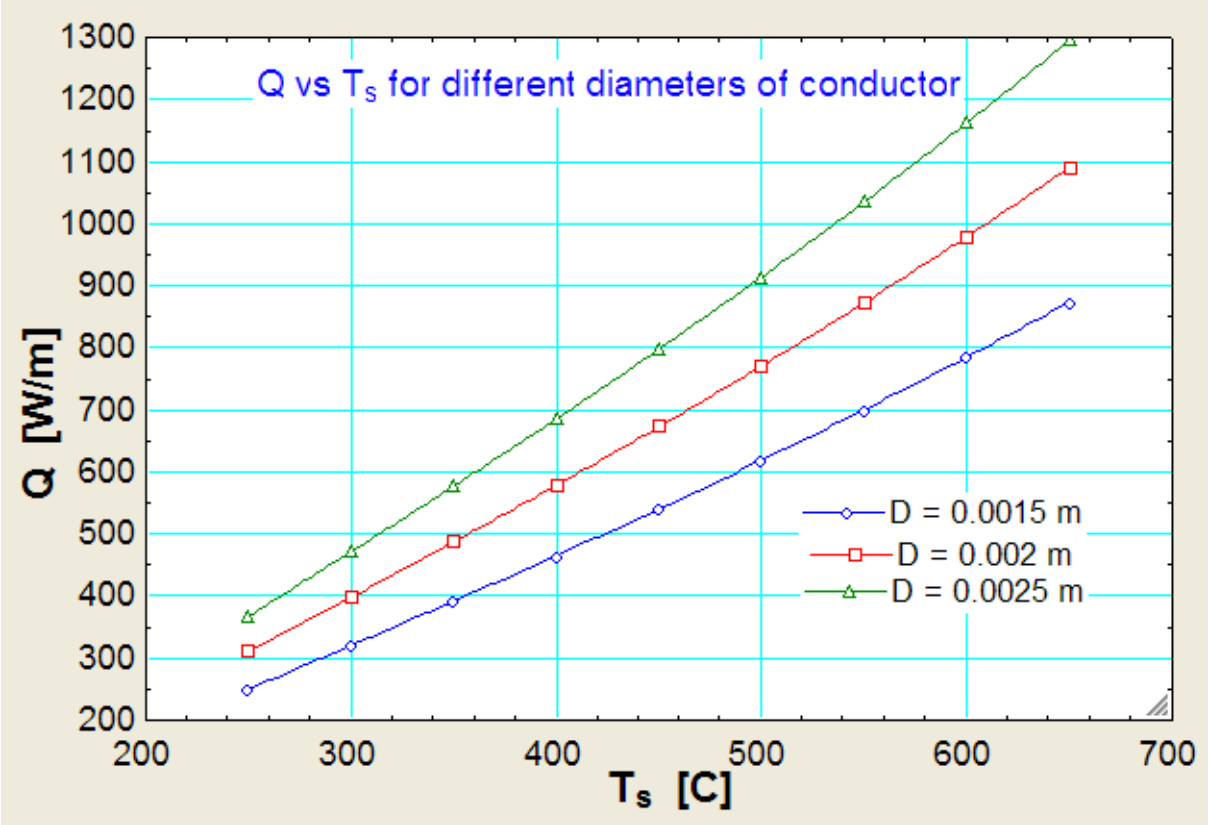
**For D = 0.0025 m:**

Table 1-D = 0.002 m | Table 2-D = 0.0015 m | Table 3-D = 0.0025 m

| 1..9 | 1 $T_s$ [C] | 2 $h_{film}$ [W/m2-C] | 3 $h_{rad}$ [W/m2-C] | 4 Q [W/m] |
|---|---|---|---|---|
| Run 1 | 250 | 303.9 | 10.48 | 367.3 |
| Run 2 | 300 | 290.7 | 12.54 | 471.4 |
| Run 3 | 350 | 282.7 | 14.89 | 576.9 |
| Run 4 | 400 | 277.7 | 17.56 | 685.3 |
| Run 5 | 450 | 274.7 | 20.56 | 797.5 |
| Run 6 | 500 | 273 | 23.93 | 914 |
| Run 7 | 550 | 272.2 | 27.68 | 1036 |
| Run 8 | 600 | 272.2 | 31.84 | 1163 |
| Run 9 | 650 | 272.6 | 36.41 | 1296 |

**Now, plot them on the same graph:**

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**Prob.3.1.15:** A 20 mm dia, 0.75 m long copper tube is used to boil saturated water at 1 atm. Find the tube surface temp if heat flux is limited to 75% of critical heat flux.

(b) Also, plot the surface temp. as function of heat flux for $0.25 < (q_s / q_{max}) < 0.90$.

**Note:** This problem is the same as Prob.3.1.4, which was solved with Mathcad.

But, now, we will solve it with EXCEL:

**EXCEL Solution:**

Following are the steps in EXCEL solution:

1. Set up the EXCEL worksheet, enter data and name the cells:

Since the heat flux, q_s is less than q_max (or, q_crit) by data, the boiling regime is Nucleate boiling (i.e. $\Delta T_e <= 30$ C).

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So, to start with, we will assume a value for T_s and later find the correct value of T_s by applying Goal Seek in EXCEL.

g | 9.81

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 209 | | | | | |
| 210 | | Data: | Fluid = | Water | |
| 211 | | Surface temp...assumed | T_s | 120 | C |
| 212 | | Sat. temp. | T_sat | 100.0 | C |
| 213 | | | n | 1.0 | For Water |
| 214 | | Radius of cyl. | Rad | 0.0100 | m |
| 215 | | Water-brass combination | C_sf | 0.013 | |
| 216 | | accn. Due to gravity | g | 9.810 | m/s^2 |

2. We need properties of Sat. water. We use the VBA Functions already written for properties of Sat. water:

sigma_L | =SatH2O_sigmaf_T((T_sat+273.15))

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 217 | | Calculations: | | | |
| 218 | | density_liq | rho_L | 957.8544061 | kg/m^3 |
| 219 | | density_vap | rho_V | 0.5956 | kg/m^3 |
| 220 | | dyn. Visc_liq | mu_L | 0.000279 | N.s/m^2 |
| 221 | | th. conductivity_liq | k_L | 0.68 | W/m.C |
| 222 | | th. conductivity_vap | k_V | 0.0248 | W/m.C |
| 223 | | sp.heat_liq | cp_L | 4217 | J/kg.K |
| 224 | | sp.heat_vap | cp_V | 2029 | J/kg.K |
| 225 | | Heat of vaporization | h_fg | 2257000 | J/kg |
| 226 | | Prandtl No._liq | Pr_L | 1.76 | |
| 227 | | Surface tension | sigma_L | 0.0589 | N/m |

Using VBA Functions for Props. of Sat. water

3. Now, first, calculate the Max. or critical heat flux, q_max, for a horizontal cylinder, as shown below. The formulas used are also shown, for clarity:

q_max | =IF(R_prime>3.74,CC,DD)

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 228 | | | | | |
| 229 | | | | | |
| 230 | | | | | |
| 231 | | To calculate q_max (Max. or Critical heat flux) for horizl cyl: | | | |
| 232 | | | AA | 228179.9637 | |
| 233 | | | BB | 4.849572083 | |
| 234 | | | q_max_F | 1106575.182 | |
| 235 | | | R_prime | 3.9929 | |
| 236 | | | CC | 989278.2124 | |
| 237 | | | DD | 9.87450E+05 | |
| 238 | | | q_max | 9.89278E+05 | W/m^2 |

$R\_prime = Rad \cdot \left[\frac{g \cdot (rho\_L - rho\_V)}{sigma\_L}\right]^{0.5}$

$AA = 0.131 \cdot h_{fg} \cdot \sqrt{rho\_V}$

$BB = [sigma\_L \cdot g \cdot (rho\_L - rho\_V)]^{\frac{1}{4}}$

$CC = q\_max\_F \cdot 0.894$

$DD = \left(0.89 + 2.27 \cdot \exp\left(-3.44 \cdot \sqrt{R\_prime}\right)\right) \cdot q\_max\_F$

Remember q_max depends only on T_sat and the geometry.

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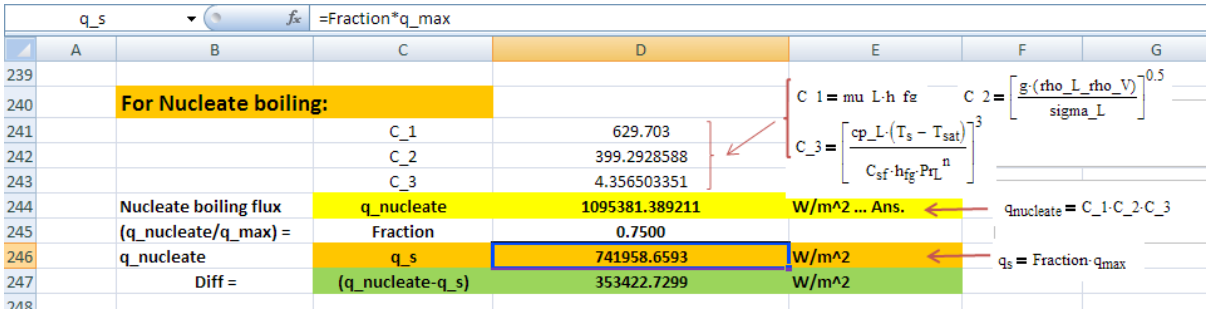
4. Now, continue the calculations for Nucleate boiling on the horizontal cylinder:



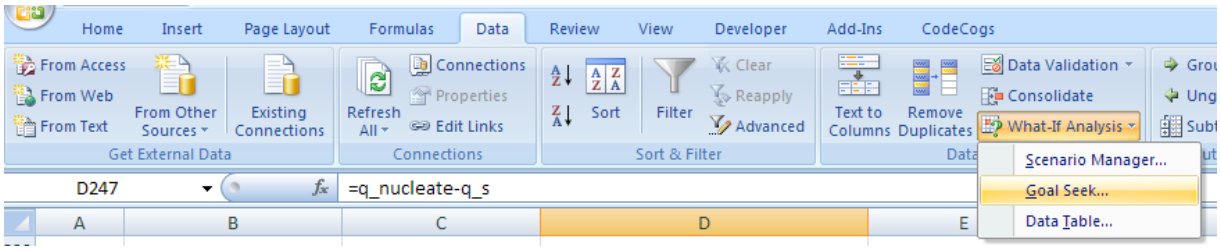

In the above, in cell D244, we have the Nucleate boiling flux, as per the equations provided.

The, in cell D246, we have q_s (i.e. Nucleate boiling flux) as a Fraction of Q_max.

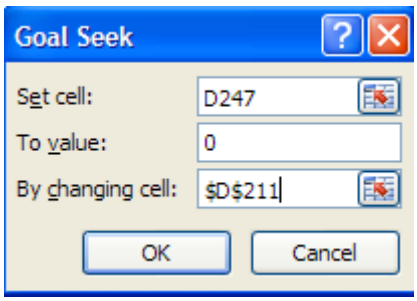
We equate them and find the required value of T_s to meet this condition i.e. cell D247 contains the difference between cells D244 and D246, and in Goal Seek operation we set it equal to zero to get correct value of T_s (i.e. cell D211).

5. Following is the Goal Seek operation:

Go to Data – WhatIf Analysis – GoalSeek:




Click on Goal Seek. You get the following screen. Fill it up as shown:

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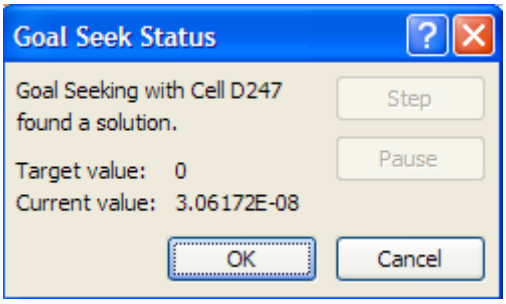
Click OK. We get:




Goal Seek has found a solution. Click OK, and see the value of T_s in cell D211 as 117.564 C.

Also, observe that all related calculations are immediately updated:

T_s | 117.564459051131

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 211 | | **Surface temp...assumed** | **T_s** | **117.5644591** | C |
| 212 | | **Sat. temp.** | **T_sat** | **100.0** | C |
| 213 | | | **n** | **1.0** | For Water |
| 214 | | **Radius of cyl.** | **Rad** | **0.0100** | m |
| 215 | | Water-brass combination | **C_sf** | **0.013** | |
| 216 | | accn. Due to gravity | **g** | **9.810** | m/s^2 |
| 217 | | **Calculations:** | | | |
| 218 | | density_liq | **rho_L** | **957.8544061** | kg/m^3 |
| 219 | | density_vap | **rho_V** | **0.5956** | kg/m^3 |
| 220 | | dyn. Visc_liq | **mu_L** | **0.000279** | N.s/m^2 |
| 221 | | th. conductivity_liq | **k_L** | **0.68** | W/m.C |
| 222 | | th. conductivity_vap | **k_V** | **0.0248** | W/m.C |
| 223 | | sp.heat_liq | **cp_L** | **4217** | J/kg.K |
| 224 | | sp.heat_vap | **cp_V** | **2029** | J/kg.K |
| 225 | | Heat of vaporization | **h_fg** | **2257000** | J/kg |
| 226 | | Prandtl No._liq | **Pr_L** | **1.76** | |
| 227 | | Surface tension | **sigma_L** | **0.0589** | N/m |
| 228 | | | | | |

And:

D247 | =q_nucleate-q_s

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 238 | | | q_max | 9.89278E+05 | W/m^2 | | |
| 239 | | | | | | | |
| 240 | | **For Nucleate boiling:** | | | | | |
| 241 | | | C_1 | 629.703 | | | |
| 242 | | | C_2 | 399.2928588 | | | |
| 243 | | | C_3 | 2.950885799 | | | |
| 244 | | Nucleate boiling flux | q_nucleate | 741958.659311 | W/m^2 ... Ans. | | |
| 245 | | (q_nucleate/q_max) = | Fraction | 0.7500 | | | |
| 246 | | q_nucleate | q_s | 741958.6593 | W/m^2 | | |
| 247 | | Diff = | (q_nucleate-q_s) | 3.06172E-08 | W/m^2 | | |

$C_1 = mu\_L \cdot h_{fg}$ $\quad C_2 = \left[\frac{g\cdot(rho\_L - rho\_V)}{sigma\_L}\right]^{0.5}$

$C_3 = \left[\frac{cp\_L\cdot(T_s - T_{sat})}{C_{sf}\cdot h_{fg}\cdot Pr_L^{\,n}}\right]^3$

$q_{nucleate} = C_1 \cdot C_2 \cdot C_3$

$q_s = Fraction \cdot q_{max}$

**Thus: Tube surface temp when q_s is 75% of q_max is: T_s = 117.564 C … Ans.**

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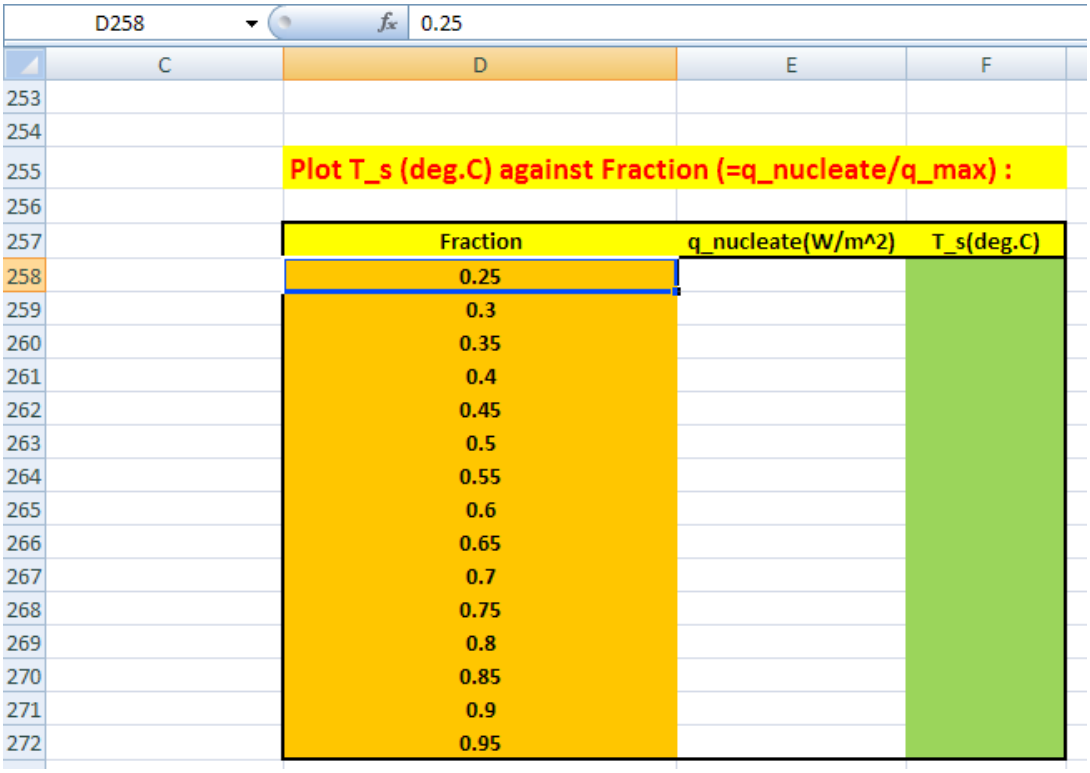
**To plot the surface temp. as function of heat flux for 0.25 < (qs / qmax) < 0.90:**

6. First, set up a Table containing the values of Fraction, as shown:



D258 | fx | 0.25

| | C | D | E | F |
|---|---|---|---|---|
| 253 | | | | |
| 254 | | | | |
| 255 | | Plot T_s (deg.C) against Fraction (=q_nucleate/q_max) : | | |
| 256 | | | | |
| 257 | | Fraction | q_nucleate(W/m^2) | T_s(deg.C) |
| 258 | | 0.25 | | |
| 259 | | 0.3 | | |
| 260 | | 0.35 | | |
| 261 | | 0.4 | | |
| 262 | | 0.45 | | |
| 263 | | 0.5 | | |
| 264 | | 0.55 | | |
| 265 | | 0.6 | | |
| 266 | | 0.65 | | |
| 267 | | 0.7 | | |
| 268 | | 0.75 | | |
| 269 | | 0.8 | | |
| 270 | | 0.85 | | |
| 271 | | 0.9 | | |
| 272 | | 0.95 | | |

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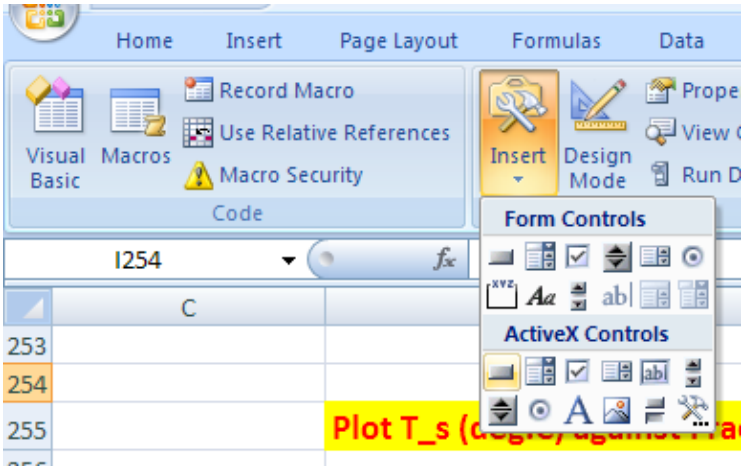
Now, we shall write a small VBA program to read these values of Fraction, one at a time, and copy to cell D245. Then immediately cell D246 (= Fraction * q_max) will change and the the difference, Diff in cell D247 will also change. Now, apply Goal Seek to make cell D247 zero by changing cell D211 (i.e. value of T_s). When this is done, all other related values will get immediately updated. Now, copy the values of q_Nucleate and T_s to their respective places in the Table.

And this program should be executed with a Command Button:

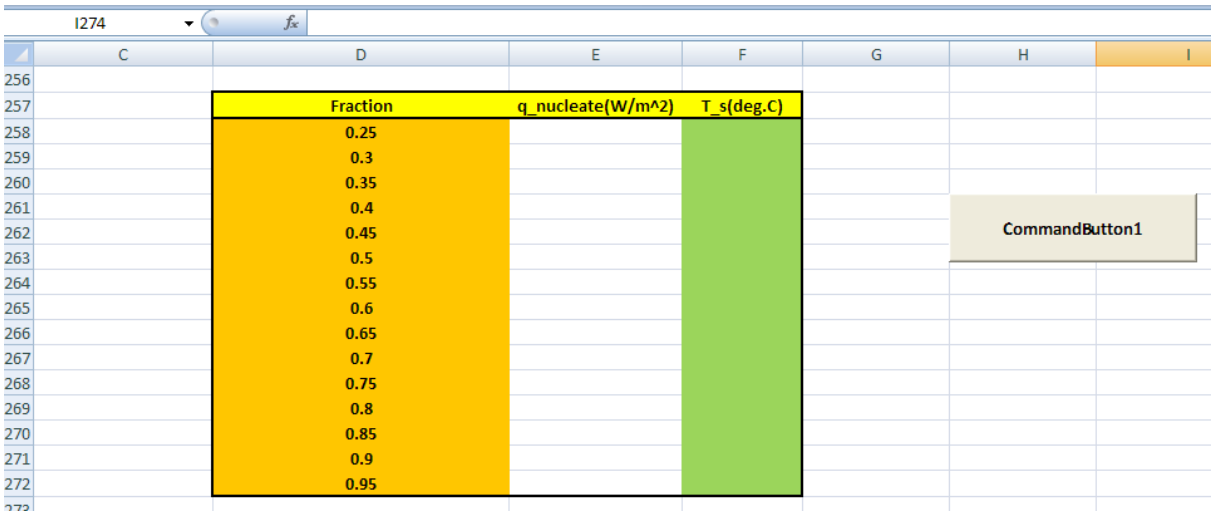
Let us write the VBA program to do the above jobs:

First, to set up the Command Button:

Go to Developer – Insert – ActiveX controls:




Click on first top left button. And, draw the Command Button in the worksheet to the required size, at the required place:

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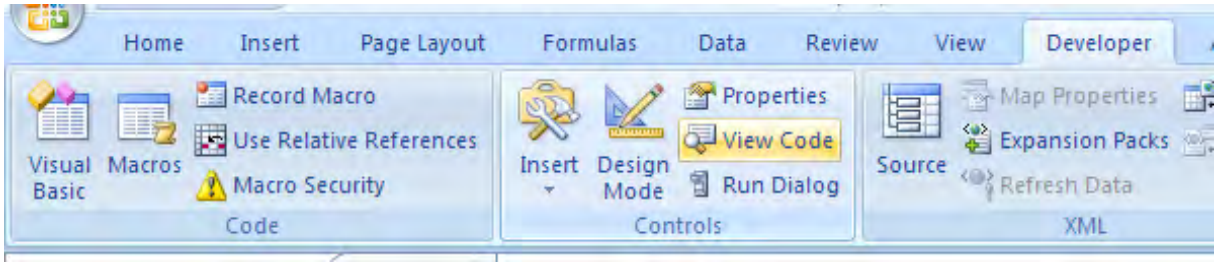
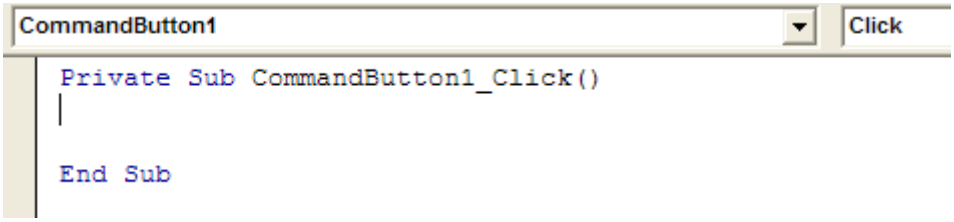
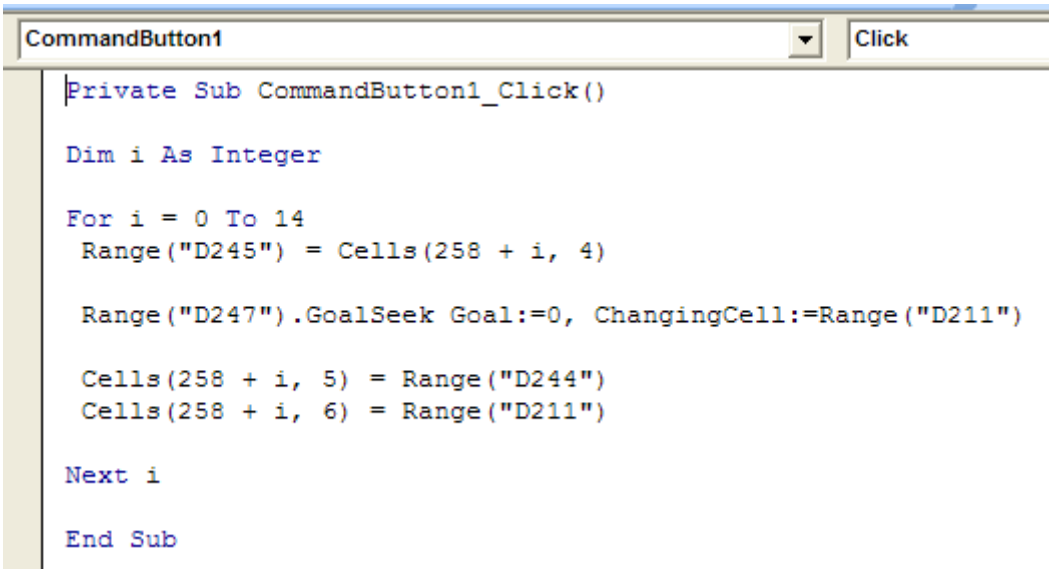
Click on Developer-View Code:




And, we get the code already written for the Command button:




Now, complete the code to do the desired jobs as mentioned under point 4 above:

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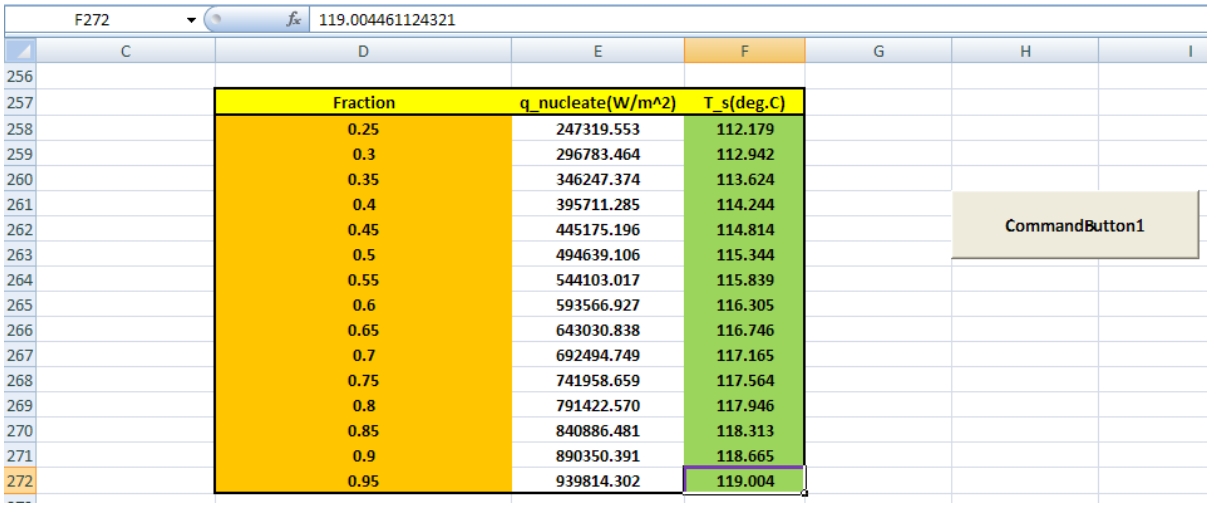
7. Now, click on the Command Button to execute the program. The Table gets filled up immediately:



F272 | 119.004461124321

| | C | D | E | F | G | H | I |
|---|---|---|---|---|---|---|---|
| 256 | | | | | | | |
| 257 | | Fraction | q_nucleate(W/m^2) | T_s(deg.C) | | | |
| 258 | | 0.25 | 247319.553 | 112.179 | | | |
| 259 | | 0.3 | 296783.464 | 112.942 | | | |
| 260 | | 0.35 | 346247.374 | 113.624 | | | |
| 261 | | 0.4 | 395711.285 | 114.244 | | CommandButton1 | |
| 262 | | 0.45 | 445175.196 | 114.814 | | | |
| 263 | | 0.5 | 494639.106 | 115.344 | | | |
| 264 | | 0.55 | 544103.017 | 115.839 | | | |
| 265 | | 0.6 | 593566.927 | 116.305 | | | |
| 266 | | 0.65 | 643030.838 | 116.746 | | | |
| 267 | | 0.7 | 692494.749 | 117.165 | | | |
| 268 | | 0.75 | 741958.659 | 117.564 | | | |
| 269 | | 0.8 | 791422.570 | 117.946 | | | |
| 270 | | 0.85 | 840886.481 | 118.313 | | | |
| 271 | | 0.9 | 890350.391 | 118.665 | | | |
| 272 | | 0.95 | 939814.302 | 119.004 | | | |

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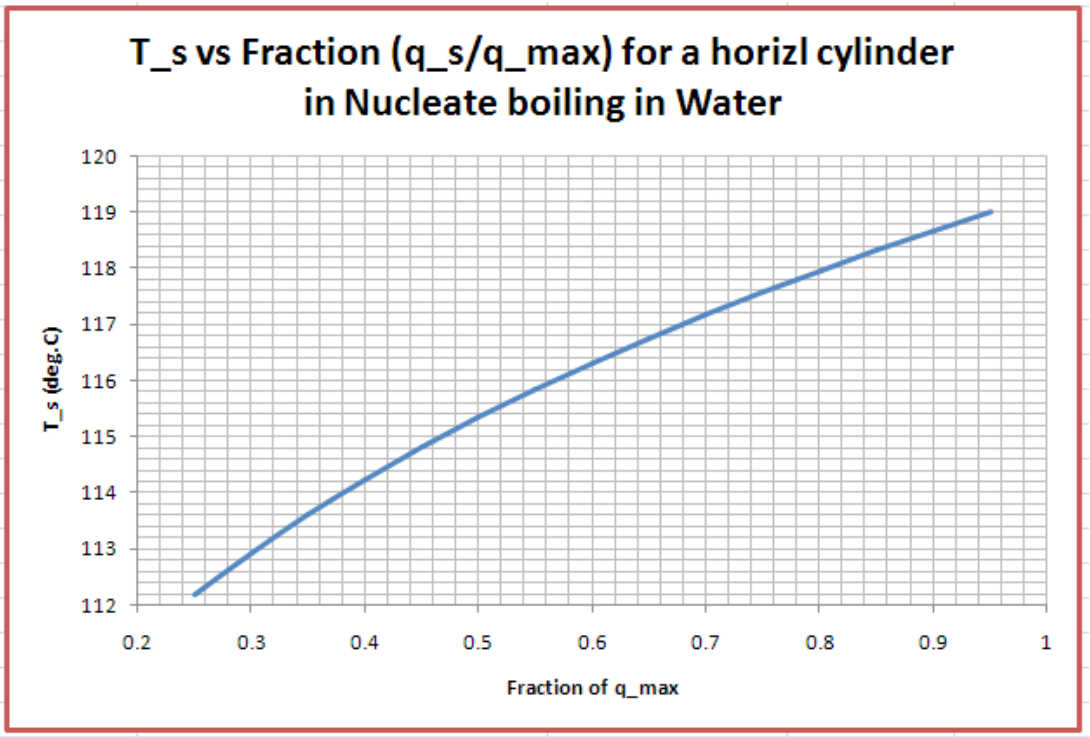
8. And, plot the graph of T_s vs Fraction in EXCEL:




Compare these results with those obtained with Mathcad:

Fraction of q_max

$\text{Fraction}^{T} =$

| | 0 |
|---|---|
| 0 | 0.25 |
| 1 | 0.3 |
| 2 | 0.35 |
| 3 | 0.4 |
| 4 | 0.45 |
| 5 | 0.5 |
| 6 | 0.55 |
| 7 | 0.6 |
| 8 | 0.65 |
| 9 | 0.7 |
| 10 | 0.75 |
| 11 | 0.8 |
| 12 | 0.85 |
| 13 | 0.9 |

$\overrightarrow{\left(T_s\left(q_{max}\cdot \text{Fraction}\right)\right)}^{T} =$

Values of Ts (C)

| | 0 |
|---|---|
| 0 | 112.179 |
| 1 | 112.942 |
| 2 | 113.624 |
| 3 | 114.244 |
| 4 | 114.814 |
| 5 | 115.344 |
| 6 | 115.839 |
| 7 | 116.305 |
| 8 | 116.746 |
| 9 | 117.165 |
| 10 | 117.564 |
| 11 | 117.946 |
| 12 | 118.313 |
| 13 | 118.665 |

**We find that the results match very well.**

==========

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**Prob.3.1.16:** A 1 mm dia wire, 150 mm long, is submerged horizontally in water at atm pressure. A steady state voltage of 10 V is applied, and the current flowing is 52.5 A. Find the surface temp of the wire.

**EXCEL Solution:**

It is convenient to make calculations if we have **VBA Functions for Boiling heat transfer calculations.**

So, let us write a few VBA Functions for Nucleate Boiling flux, Max. flux, Film boiling heat transfer coeff. etc.

But, for Film boiling calculations, we need the vapour properties of superheated water vapour (i.e. steam) at different temps and (mostly) at 1 atm.

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So, first, we use the properties of steam at 1 atm given in Incropera (Ref: 3) and write VBA Functions for properties of Steam:

| | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|
| 143 | **Properties of Steam (Ref: Incropera, p.921)** | | | | | | | |
| 144 | | | | | | | | |
| 145 | T (K) | rho (kg/m^3) | cp (kJ/kg.K) | mu*10^7 (N.s/m^2) | nu*10^6 (m^2/s) | k*10^3 (W/m.K) | alpha*10^6 (m^2/s) | Pr |
| 146 | 380 | 0.5863 | 2.06 | 127.1 | 21.68 | 24.6 | 20.4 | 1.06 |
| 147 | 400 | 0.5542 | 2.014 | 134.4 | 24.25 | 26.1 | 23.4 | 1.04 |
| 148 | 450 | 0.4902 | 1.98 | 152.5 | 31.11 | 29.9 | 30.8 | 1.01 |
| 149 | 500 | 0.4405 | 1.985 | 170.4 | 38.68 | 33.9 | 38.8 | 0.998 |
| 150 | 550 | 0.4005 | 1.997 | 188.4 | 47.04 | 37.9 | 47.4 | 0.993 |
| 151 | 600 | 0.3652 | 2.026 | 206.7 | 56.6 | 42.2 | 57 | 0.993 |
| 152 | 650 | 0.338 | 2.056 | 224.7 | 66.48 | 46.4 | 66.8 | 0.996 |
| 153 | 700 | 0.314 | 2.085 | 242.6 | 77.26 | 50.5 | 77.1 | 1 |
| 154 | 750 | 0.2931 | 2.119 | 260.4 | 88.84 | 54.9 | 88.4 | 1 |
| 155 | 800 | 0.2739 | 2.152 | 278.6 | 101.7 | 59.2 | 100 | 1.01 |
| 156 | 850 | 0.2579 | 2.186 | 296.9 | 115.1 | 63.7 | 113 | 1.02 |

Now, write VBA Functions for rho_v, cp_v, mu_v and k_v as functions of Temp (K). Linear interpolation is used to get the properties at the required temp.

**For rho_v:**

```
Function Steam_rho_T(T As Double) As Double
'gives density of steam (water vap.)(kg/m^3)as a function of T (K) at 1 atm.
'Reads rho values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rho_1 As Double, rho_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_rho_T = Cells(146 + i, 13)
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      rho_1 = Cells(146 + i, 13).Value
      rho_2 = Cells(146 + i + 1, 13).Value
      Steam_rho_T = (rho_1 + (T - T_1) * (rho_2 - rho_1) / (T_2 - T_1))
   End If

Next i

End Function
```

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**For cp_v:**

```
Function Steam_cp_T(T As Double) As Double
'gives sp. heat of steam (water vap.)(J/kg.K)as a function of T (K) at 1 atm.
'Reads cp values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, cp_1 As Double, cp_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_cp_T = Cells(146 + i, 14) * 10 ^ -3
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      cp_1 = Cells(146 + i, 14).Value
      cp_2 = Cells(146 + i + 1, 14).Value
      Steam_cp_T = (cp_1 + (T - T_1) * (cp_2 - cp_1) / (T_2 - T_1)) * 10 ^ -3
   End If

Next i

End Function
```

**For mu_v:**

```
Function Steam_mu_T(T As Double) As Double
'gives dyn. visc. of steam (water vap.)(N.s/m^2)as a function of T (K) at 1 atm.
'Reads mu values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, mu_1 As Double, mu_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_mu_T = Cells(146 + i, 15) * 10 ^ -7
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      mu_1 = Cells(146 + i, 15).Value
      mu_2 = Cells(146 + i + 1, 15).Value
      Steam_mu_T = (mu_1 + (T - T_1) * (mu_2 - mu_1) / (T_2 - T_1)) * 10 ^ -7
   End If

Next i

End Function
```

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**For k_v:**

```
Function Steam_k_T(T As Double) As Double
'gives thermal cond. of steam (water vap.)(W/m.K)as a function of T (K) at 1 atm.
'Reads k values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, k_1 As Double, k_2 As Double

If T < 380 Or T > 850 Then

 MsgBox ("T must be between 380 K and 850 K !!")
 End
 End If

For i = 0 To 10

   If Cells(146 + i, 12) = T Then
      Steam_k_T = Cells(146 + i, 17) * 10 ^ -3
   End If
   If Cells(146 + i, 12) < T And Cells(146 + i + 1, 12) > T Then
      T_1 = Cells(146 + i, 12).Value
      T_2 = Cells(146 + i + 1, 12).Value
      k_1 = Cells(146 + i, 17).Value
      k_2 = Cells(146 + i + 1, 17).Value
      Steam_k_T = (k_1 + (T - T_1) * (k_2 - k_1) / (T_2 - T_1)) * 10 ^ -3
   End If

Next i

End Function
```

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**Now. have VBA Functions for Boiling heat transfer calculations:**

1. **For Nucleate boiling flux:**

```
Function Boiling_water_q_nucleate(T_s As Double, T_sat As Double, C_sf As Double) As Double
'Returns q_nucleate for Water boiling at 1 atm
'Input: T_s (C), T_sat (C), C_sf from Table
'Output: q_nucleate (W/m^2)
'Valid for any geometry
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double
Dim n As Integer
Dim AA As Double, BB As Double, CC As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity
n = 1

'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)

AA = mu_l * h_fg
BB = (g * (rho_l - rho_v) / sigma) ^ (1 / 2)
CC = (cp_l * (T_s - T_sat) / (C_sf * h_fg * Pr_l ^ n)) ^ 3

Boiling_water_q_nucleate = AA * BB * CC


End Function
```

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2. **For Max. flux on a horizontal surface:**

```
Function Boiling_water_HorizlSurface_q_max(T_sat As Double) As Double
'Returns q_maxfor Water boiling at 1 atm, on a large, flat surface
'Input: T_s (C), T_sat (C), C_sf from Table
'Output: q_max(W/m^2)
'Valid for large, flat surface
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)


AA = 0.149 * h_fg
BB = (sigma * g * rho_v ^ 2 * (rho_l - rho_v)) ^ (1 / 4)

 Boiling_water_HorizlSurface_q_max = AA * BB


End Function
```

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3. **For Max. flux on a horizontal cylinder:**

```
Function Boiling_water_HorizlCylinder_q_max(T_sat As Double, Rad As Double) As Double
'Returns q_max for Water boiling at 1 atm, on a horizl cylinder
'Input: T_sat (C), Radius (m)
'Output: q_max(W/m^2)
'Valid for horizl cyl
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double, R_prime As Double, q_max_F As Double

Dim AA As Double

Dim rho_l As Double, rho_v As Double, k_l As Double, mu_l As Double
Dim Pr_l As Double
Dim cp_l As Double, h_fg As Double, sigma As Double

g = 9.81 'm/s^2....accn due to gravity


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
k_l = SatH2O_kf_T(T_sat + 273.15)
mu_l = SatH2O_muf_T(T_sat + 273.15)
cp_l = SatH2O_cpf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)
Pr_l = SatH2O_Prf_T(T_sat + 273.15)


R_prime = Rad * (g * (rho_l - rho_v) / sigma) ^ 0.5

q_max_F = 0.131 * (rho_v) ^ 0.5 * h_fg * (sigma * g * (rho_l - rho_v)) ^ (1 / 4)

AA = 0.89 + 2.27 * Exp(-3.44 * R_prime ^ 0.5)

If R_prime > 3.47 Then

   Boiling_water_HorizlCylinder_q_max = 0.894 * q_max_F

End If

If (R_prime >= 0.15) And (R_prime <= 3.47) Then

   Boiling_water_HorizlCylinder_q_max = q_max_F * AA

End If


End Function
```

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4. **For Film boiling on a horizontal surface-heat tr. coeff. h_film:**

```
Function Boiling_water_HorizlSurface_h_film(T_s As Double, T_sat As Double) As Double
'Returns h_film (W/m^2.C)for film boiling with water at 1 atm, on a Horizl surface
'Input: T_s, T_sat (C)
'Valid for Horizl surface
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double

Dim Lambda As Double, C_0 As Double, h_fg_prime As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_v As Double, mu_v As Double
Dim T_f As Double
Dim cp_v As Double, h_fg As Double, sigma As Double

If (T_s - T_sat) <= 30 Then

  MsgBox ("Use Nucleate Boiling correlations since (T_s - T_sat) <= 30 C !!")

  End

End If

g = 9.81 'm/s^2....accn due to gravity

T_f = (T_s + T_sat) / 2

'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)

'For props of vapour:

rho_v = Steam_rho_T(T_f + 273.15)
cp_v = Steam_cp_T(T_f + 273.15)
k_v = Steam_k_T(T_f + 273.15)
mu_v = Steam_mu_T(T_f + 273.15)

Lambda = 2 * Application.Pi() * (sigma / (g * (rho_l - rho_v))) ^ 0.5

C_0 = 0.59

h_fg_prime = h_fg + 0.4 * cp_v * (T_s - T_sat)

AA = (h_fg_prime * g * rho_v * (rho_l - rho_v) * k_v ^ 3)

BB = mu_v * (T_s - T_sat) * Lambda

 Boiling_water_HorizlSurface_h_film = C_0 * (AA / BB) ^ (1 / 4)

End Function
```

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5. **For Film boiling on a horizontal cylinder-heat tr. coeff. h_film:**

```
Function Boiling_water_HorizlCyl_h_film(T_s As Double, T_sat As Double, D As Double) As Double
'Returns h_film (W/m^2.C)for film boiling with water at 1 atm, on a Horizl cyl
'Input: T_s, T_sat (C), Dia D (m)
'Valid for Horizl cyl
'Reads property values of Water from Table and interpolates using VBA Functions


Dim g As Double


Dim C_0 As Double, h_fg_prime As Double

Dim AA As Double, BB As Double

Dim rho_l As Double, rho_v As Double, k_v As Double, mu_v As Double
Dim T_f As Double
Dim cp_v As Double, h_fg As Double, sigma As Double

If (T_s - T_sat) <= 30 Then

  MsgBox ("Use Nucleate Boiling correlations since (T_s - T_sat) <= 30 C !!")

  End

End If

g = 9.81 'm/s^2....accn due to gravity

T_f = (T_s + T_sat) / 2


'Properties of Water at T_sat:

rho_l = 1 / SatH2O_vf_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
sigma = SatH2O_sigmaf_T(T_sat + 273.15)

'For props of vapour:

rho_v = Steam_rho_T(T_f + 273.15)
cp_v = Steam_cp_T(T_f + 273.15)
k_v = Steam_k_T(T_f + 273.15)
mu_v = Steam_mu_T(T_f + 273.15)


C_0 = 0.62

h_fg_prime = h_fg + 0.4 * cp_v * (T_s - T_sat)

AA = (h_fg_prime * g * rho_v * (rho_l - rho_v) * k_v ^ 3)

BB = mu_v * (T_s - T_sat) * D

 Boiling_water_HorizlCyl_h_film = C_0 * (AA / BB) ^ (1 / 4)

End Function
```

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**Now, let us solve the problem: Let us state the problem again:**

**Prob.3.1.16:** A 1 mm dia nickel wire, 150 mm long, is submerged horizontally in water at atm pressure. A steady state voltage of 10 V is applied, and the current flowing is 52.5 A. Find the surface temp of the wire.

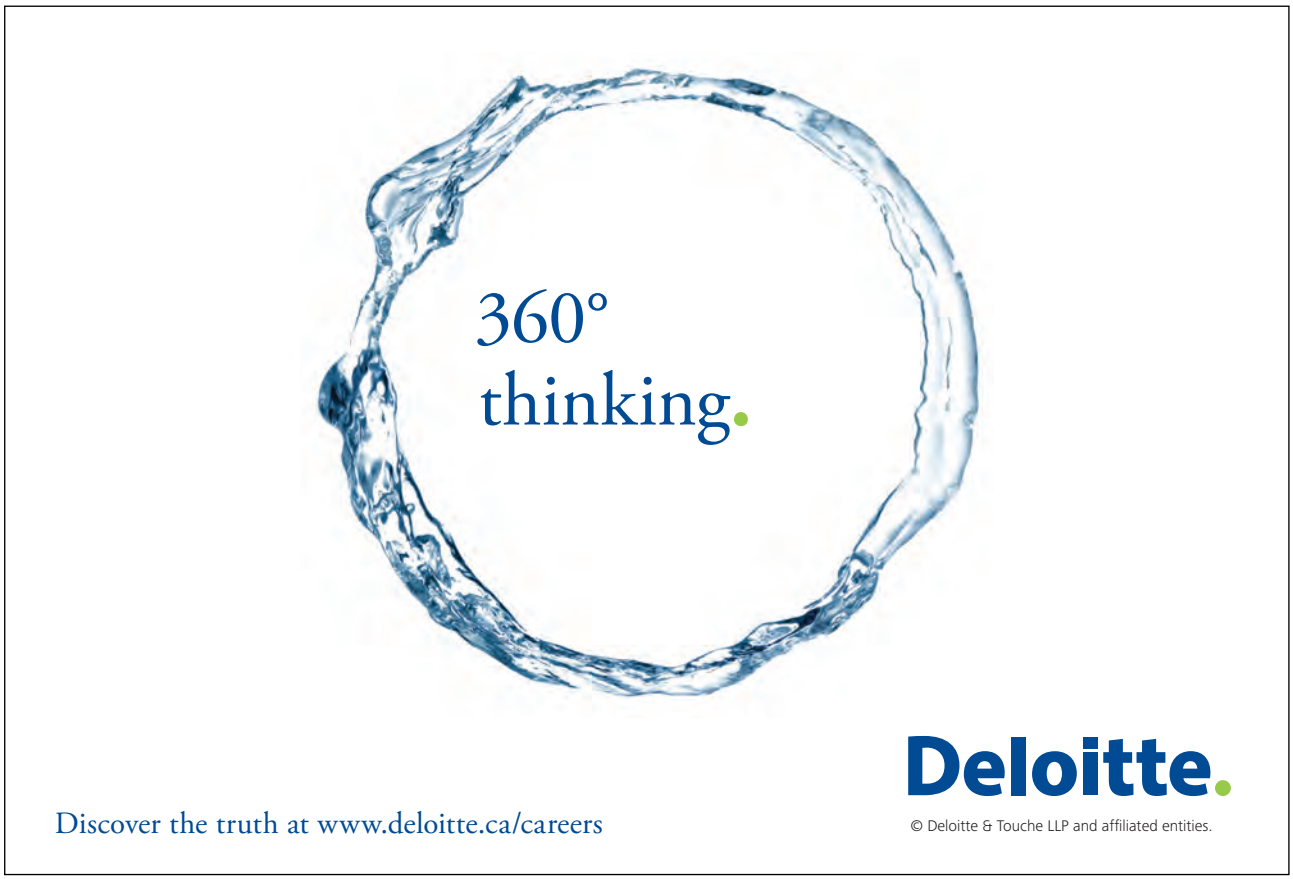
**EXCEL Solution:**

Here, Voltage and current are given. Therefore, Total Power, Q = (V . I) is calculated. Then, (Q/Surface area) of wire gives the surface heat flux. This should be equal to the Nucleate boiling heat flux, assuming that boiling is in the Nucleate boiling regime. Goal Seek is used to find the value of T_s.

1. Set up the Excel worksheet, enter data:

D302 | 120

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 300 | | | | | |
| 301 | | **Data:** | **Fluid =** | **Water** | |
| 302 | | **Surface temp...assumed** | **T_s** | **120** | C |
| 303 | | **Sat. temp.** | **T_sat** | **100.0** | C |
| 304 | | **Radius of cyl.** | **Rad** | **0.0005** | m |
| 305 | | Water-nickel combination | **C_sf** | **0.006** | From Table |
| 306 | | Length of wire | **L** | **0.15** | m |
| 307 | | Voltage | **V** | **10.000** | V |
| 308 | | Current | **I** | **52.5** | A |

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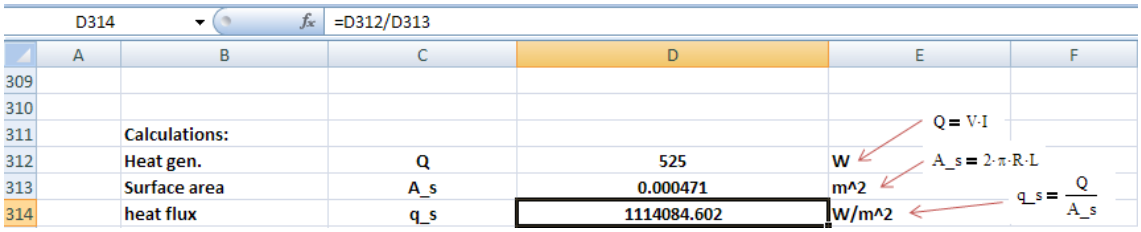
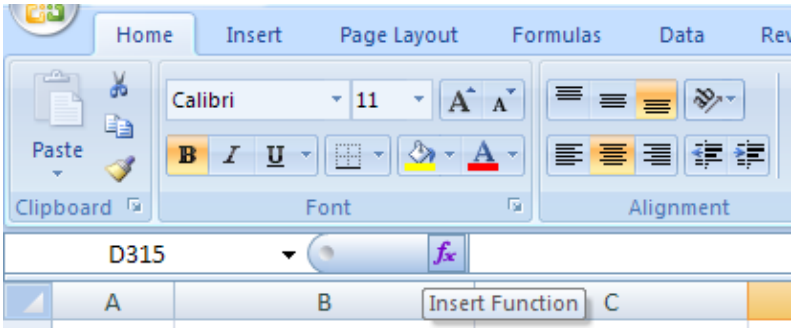
2. Calculate the surface heat flux from the given values of V, I etc.:



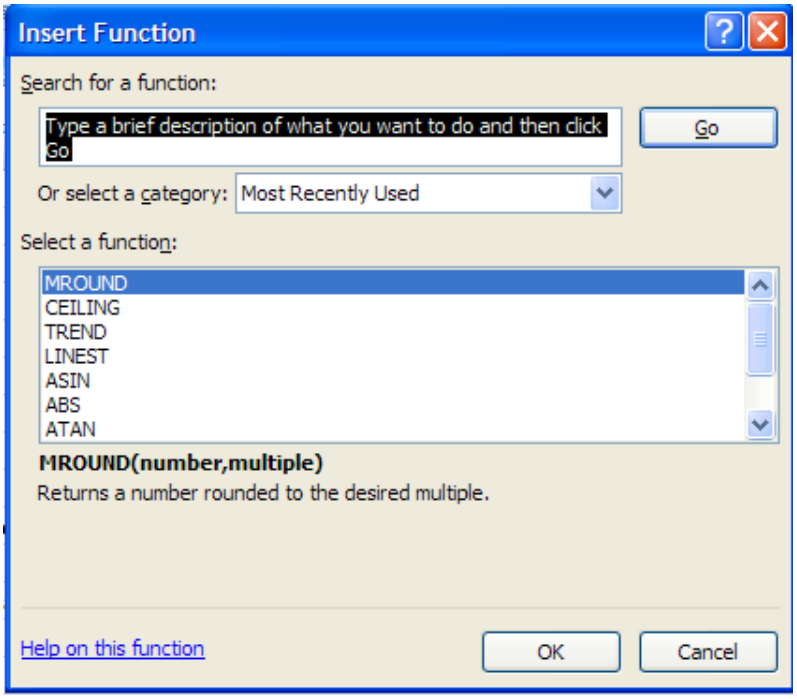

3. Now, **q_nucleate is calculated using the VBA Function for Nucleate boiling flux, written earlier**.

To insert the VBA Function for q_nucleate in cell D315, we do the following:

Select cell D315. Then locate the 'Insert Function' symbol as shown below:




Click on Insert Function symbol. We get:

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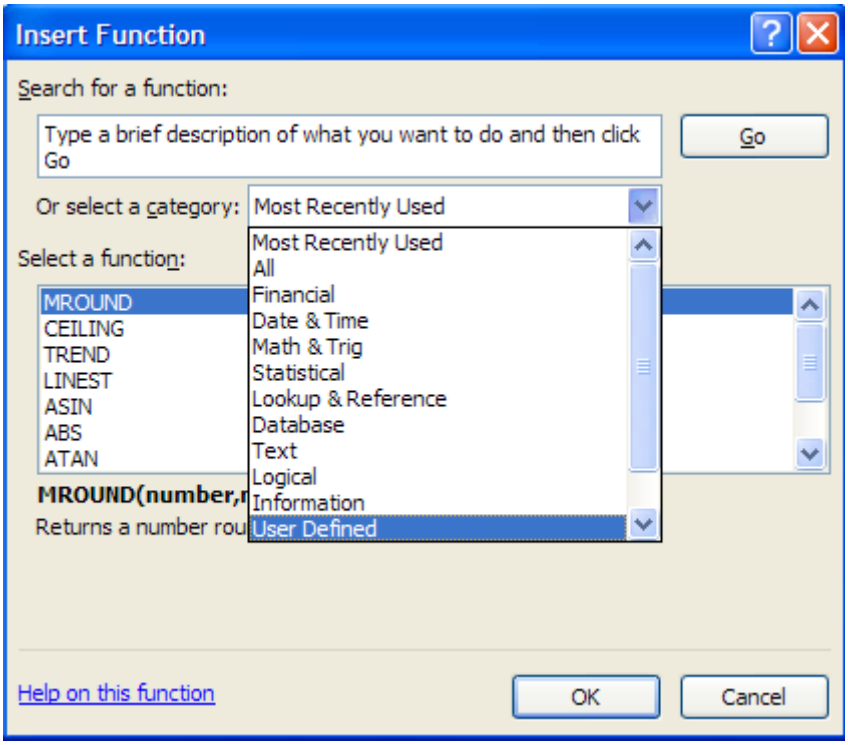
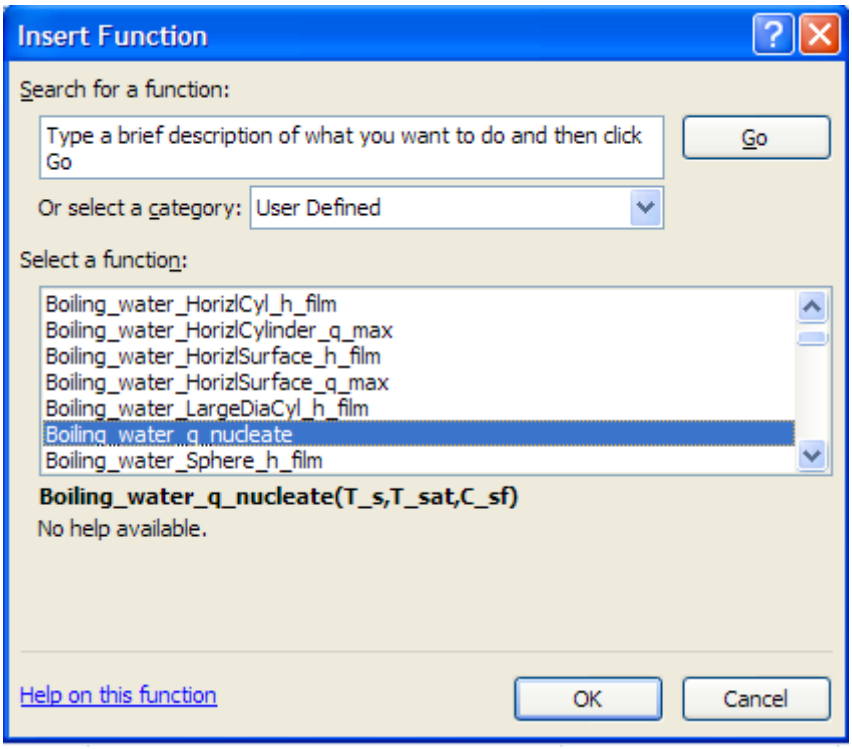
Under Category: select 'User Defined':




Click on 'User Defined'. Several built-in Functions appear. Choose 'Boiling_Water_q_nucleate':

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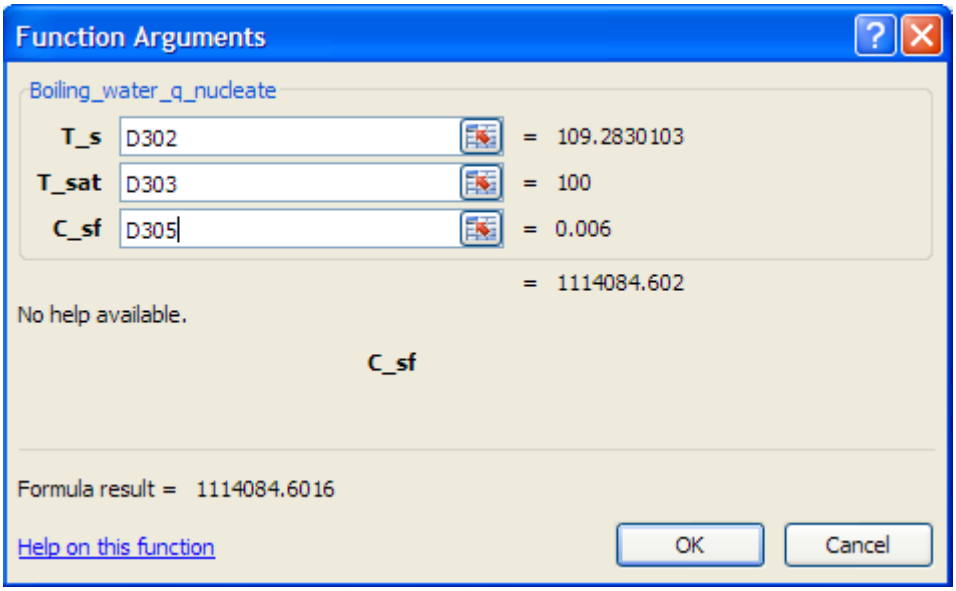
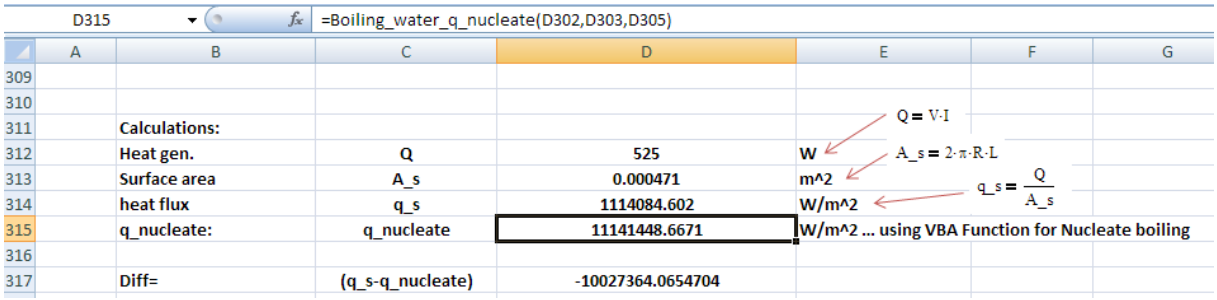
Click OK. We get the following screen. Fill it up as shown:



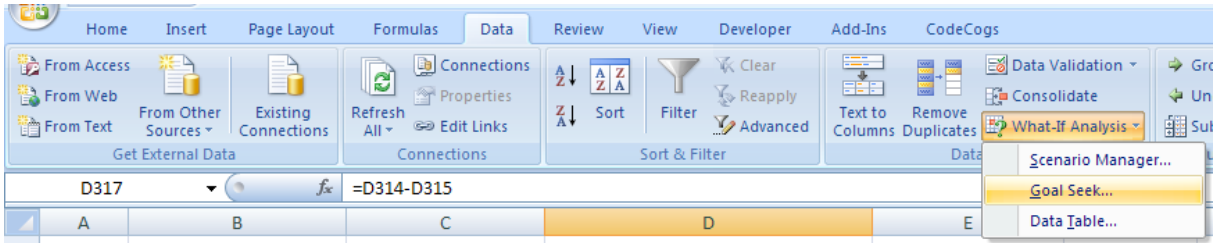

Click OK. The Function is inserted in cell D315:




Then, in cell D317, we have the difference = (q_s – q_nucleate), which should be equal to zero. So, use Goal Seek to make cell D317 equal to zero by changing cell D302 (i.e. T_s):

4. Following is the procedure:

Go to Data – WhatIf Analysis – Goal Seek:

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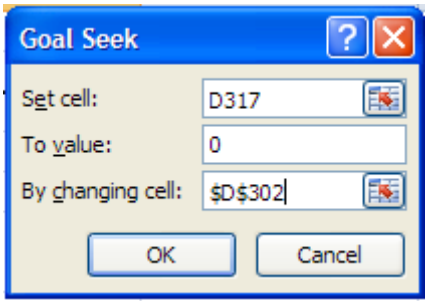
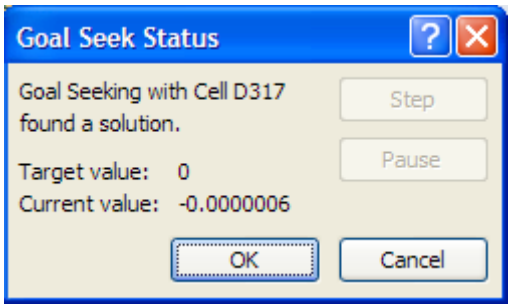
Click on Goal Seek. Fill up the screen that appears as follows:




Click OK. We get:



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Goal seek has found a solution. Click OK. We get:

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 300 | | | | | | | |
| 301 | | Data: | Fluid = | Water | | | |
| 302 | | Surface temp...assumed | T_s | 109.2830103 | C | | |
| 303 | | Sat. temp. | T_sat | 100.0 | C | | |
| 304 | | Radius of cyl. | Rad | 0.0005 | m | | |
| 305 | | Water-nickel combination | C_sf | 0.006 | From Table | | |
| 306 | | Length of wire | L | 0.15 | m | | |
| 307 | | Voltage | V | 10.000 | V | | |
| 308 | | Current | I | 52.5 | A | | |
| 309 | | | | | | | |
| 310 | | | | | | | |
| 311 | | Calculations: | | | $Q = V \cdot I$ | | |
| 312 | | Heat gen. | Q | 525 | W | | |
| 313 | | Surface area | A_s | 0.000471 | m^2 | $A_s = 2 \cdot \pi \cdot R \cdot L$ | |
| 314 | | heat flux | q_s | 1114084.602 | W/m^2 | $q_s = \frac{Q}{A_s}$ | |
| 315 | | q_nucleate: | q_nucleate | 1114084.6016 | W/m^2 ... using VBA Function for Nucleate boiling | | |
| 316 | | | | | | | |
| 317 | | Diff= | (q_s-q_nucleate) | -0.0000006 | | | |

**Thus: T_s = 109.283 C …. Ans.**

==========

**Prob.3.1.17:** In a laboratory experiment, a 1 mm dia, 30 cm long nickel wire is submerged horizontally in water at 1 atm, and burn-out occurs when a current of 193 A is passed. What is the voltage at burn-out?

**EXCEL Solution:**

Here, we first assume the voltage and calculate the surface heat flux. Then we use the VBA Function to get burn-out (or, Max.) flux for a cylinder and use Goal Seek to find the voltage such that the two heat fluxes are equal:

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 324 | | Data: | Fluid = | Water | |
| 325 | | | | | |
| 326 | | Sat. temp. | T_sat | 100.0 | C |
| 327 | | Radius of cyl. | Rad | 0.0005 | m |
| 328 | | | | | |
| 329 | | Length of wire | L | 0.3 | m |
| 330 | | Voltage ... assumed | V | 10.000 | V |
| 331 | | Current | I | 193 | A |

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2. Calculate the surface heat flux from given data. Also, calculate the burn-out (or, Max.) heat flux from the VBA Function written earlier:

D338 =Boiling_water_HorizlCylinder_q_max(D326,D327)

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 333 | | | | | | | |
| 334 | | Calculations: | | | | | |
| 335 | | Heat gen. | Q | 1930 | W | | |
| 336 | | Surface area | A_s | 0.000942 | m^2 | | |
| 337 | | heat flux | q_s | 2047793.601 | W/m^2 | | |
| 338 | | Max. heat flux: | q_max | 1524949.916 | W/m^2...from VBA Function for Max. heat flux | | |
| 339 | | Diff = | (q_s - q_max) | 522843.685 | W?m^2 | | |
| 340 | | | | | | | |

$Q = V \cdot I$

$A_s = 2 \cdot \pi \cdot R \cdot L$

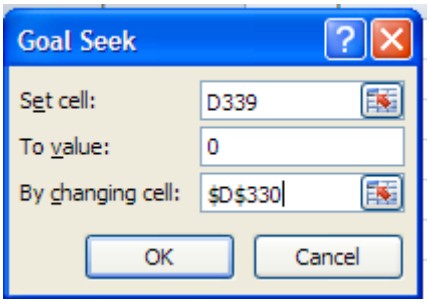
$q_s = \frac{Q}{A_s}$

In the above, in cell D338, q_max is calculated using the VBA Function for q_max for a horizontal cylinder. See the previous problem for the procedure to insert the VBA Function. The eqn can be seen in the Formula bar.

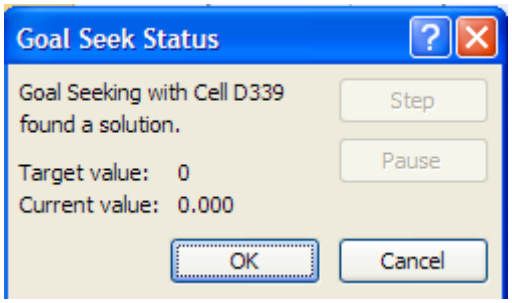
3. Now, in cell D339, we have the difference: (q_s – q_max), which should be equal to zero. So, apply Goal Seek to make cell D339 equal to zero by changing cell D330 (i.e. vlue of voltage, V):

For procedure of Goal Seek, see problem 3.1.16.

We get:




Click OK. We get:

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And, the result is:

D339 =D337-D338

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 324 | | Data: | Fluid = | Water | | | |
| 325 | | | | | | | |
| 326 | | Sat. temp. | T_sat | 100.0 | C | | |
| 327 | | Radius of cyl. | Rad | 0.0005 | m | | |
| 328 | | | | | | | |
| 329 | | Length of wire | L | 0.3 | m | | |
| 330 | | Voltage ... assumed | V | 7.447 | V | | |
| 331 | | Current | I | 193 | A | | |
| 332 | | | | | | | |
| 333 | | | | | | | |
| 334 | | Calculations: | | | $Q = V \cdot I$ | | |
| 335 | | Heat gen. | Q | 1437.231436 | W | | |
| 336 | | Surface area | A_s | 0.000942 | m^2 | $A_s = 2 \cdot \pi \cdot R \cdot L$ | |
| 337 | | heat flux | q_s | 1524949.916 | W/m^2 | $q_s = \frac{Q}{A_s}$ | |
| 338 | | Max. heat flux: | q_max | 1524949.916 | W/m^2...from VBA Function for Max. heat flux | | |
| 339 | | Diff = | (q_s - q_max) | 0.000 | W?m^2 | | |
| 340 | | | | | | | |

**Thus: the voltage at burn-out is: 7.447 V….Ans.**

==========

**Prob.3.1.18:** A steel bar, 20 mm in diameter and 200 mm long, with an emissivity of 0.9, is removed from a furnace at 455 C and suddenly submerged in a water bath under atmospheric pressure. Estimate the initial heat transfer rate from the bar.

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**EXCEL Solution:**

It is obviously heat transfer in the Film boiling region since $\Delta T_e > 30$ C.

We shall use the VBA Function written above to get film boiling heat transfer coeff. for a horizontal cylinder.

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 345 | | Data: | Fluid = | Water | |
| 346 | | Surface temp | T_s | 455 | C |
| 347 | | Sat. temp. | T_sat | 100.0 | C |
| 348 | | Dia of cylinder | D | 0.0200 | m |
| 349 | | Length of cyl | L | 0.2 | m |
| 350 | | emissivity | epsilon | 0.9 | |
| 351 | | Stefan Boltzmann const. | sigma | 5.67E-08 | W/m^2.K^4 |
| 352 | | | | | |

2. Find the film boiling heat transfer coeff. h_film using the VBA Function. Then, calculate the Q_boiling and also the Q_radn, and add them up. Formulas used are also shown, in the following worksheet, for clarity:

D357 =Boiling_water_HorizlCyl_h_film(D346,D347,D348)

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 345 | | Data: | Fluid = | Water | | | |
| 346 | | Surface temp | T_s | 455 | C | | |
| 347 | | Sat. temp. | T_sat | 100.0 | C | | |
| 348 | | Dia of cylinder | D | 0.0200 | m | | |
| 349 | | Length of cyl | L | 0.2 | m | | |
| 350 | | emissivity | epsilon | 0.9 | | | |
| 351 | | Stefan Boltzmann const. | sigma | 5.67E-08 | W/m^2.K^4 | | |
| 352 | | | | | | | |
| 353 | | | | | | | |
| 354 | | | | | | | |
| 355 | | Calculations: | | | | | |
| 356 | | | | | | | |
| 357 | | film heat tr coeff. | h_film | 150.3956 | W/m^2.C | | |
| 358 | | boiling heat tr. rate | Q_b | 670.924 | W | | |
| 359 | | radn heat tr. rate | Q_rad | 167.7068 | W | | |
| 360 | | Total heat tr rate: | (Q_b + Q_rad) = | 838.631 | W....Ans. | | |

$Q\_b = h\_film \cdot (\pi \cdot D \cdot L) \cdot (T\_s - T\_sat)$

$Q\_rad = \sigma \cdot \varepsilon \cdot (\pi \cdot D \cdot L) \cdot \left[ (T\_s + 273)^4 - (T\_sat + 273)^4 \right]$

In the above, note in the Formula bar the Function used to calculate h_film for horizontal cylinder.

**Thus: Total initial heat transfer rate from the bar = 838.63 W ….. Ans.**

==========

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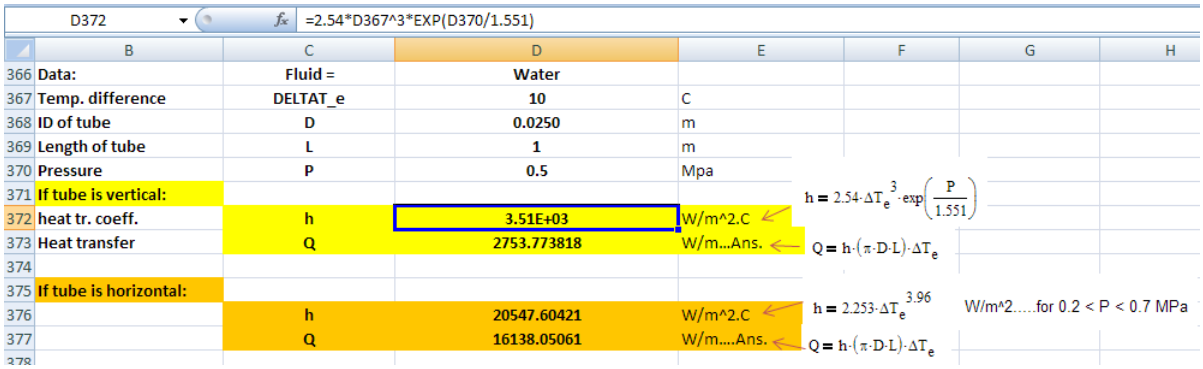
**Prob.3.1.19:** Water at 5 bar flows inside a vertical tube of 2.5 cm dia under flow boiling conditions. Tube wall temp is maintained at 10 C above the sat. temp. Determine the heat transfer for 1 m length of tube. (b) What will be the heat transfer if the tube is horizontal?

**EXCEL Solution:**

**This is an internal flow boiling problem.**

Following is the EXCEL worksheet:



D372 =2.54*D367^3*EXP(D370/1.551)

| | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|
| 366 | Data: | Fluid = | Water | | | | |
| 367 | Temp. difference | DELTAT_e | 10 | C | | | |
| 368 | ID of tube | D | 0.0250 | m | | | |
| 369 | Length of tube | L | 1 | m | | | |
| 370 | Pressure | P | 0.5 | Mpa | | | |
| 371 | If tube is vertical: | | | | $h = 2.54 \cdot \Delta T_e^{\,3} \cdot \exp\left(\frac{P}{1.551}\right)$ | | |
| 372 | heat tr. coeff. | h | 3.51E+03 | W/m^2.C | | | |
| 373 | Heat transfer | Q | 2753.773818 | W/m...Ans. | $Q = h \cdot (\pi \cdot D \cdot L) \cdot \Delta T_e$ | | |
| 374 | | | | | | | |
| 375 | If tube is horizontal: | | | | | | |
| 376 | | h | 20547.60421 | W/m^2.C | $h = 2.253 \cdot \Delta T_e^{\,3.96}$ | W/m^2.....for 0.2 < P < 0.7 MPa | |
| 377 | | Q | 16138.05061 | W/m....Ans. | $Q = h \cdot (\pi \cdot D \cdot L) \cdot \Delta T_e$ | | |

Formulas used are also shown in the worksheet.

Thus:

**For vertical tube: h = 3510 W/m^2.C, Q = 2753.8 W/m … Ans.**

**For horizontal tube: h = 20547.6 W/m^2.C, Q = 16138.1 W/m … Ans.**

==========

**Prob.3.1.20:** A 1 mm dia nickel wire, 150 mm long, is submerged horizontally in water at atm pressure. The surface temp of the wire is 110 C. Find the nucleate boiling flux.

(b) If the water is flowing normal to the wire at 3 m/s, what will be the change in heat flux?

(c) What should be the flow velocity to make convective heat flux equal to the boiling heat flux?

**EXCEL Solution:**

**This is Problem is on external flow boiling.**

First, we will find out nucleate boiling flux, $q_{boiling}$ using the VBA Function already written.

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Then, we will find out the convection flux, $q_{conv}$ using relation for cross flow of water over a cylinder.

And, total heat flux is: $q_{total} = q_{conv} + q_{boiling}$

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

C389 | fx | U_inf

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 383 | | Data: | Fluid = | Water | |
| 384 | | Surface temp | T_s | 110 | C |
| 385 | | Sat. temp. | T_sat | 100.0 | C |
| 386 | | Radius of cyl. | Rad | 0.0005 | m |
| 387 | | Water-nickel combination | C_sf | 0.006 | From Table |
| 388 | | Length of wire | L | 0.15 | m |
| 389 | | Velocity | U_inf | 3.000 | m/s |

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2. Now, calculate the nucleate boiling flux using the VBA Function in cell D393. For the method of entering the Function, see Problem 3.1.16. Following is the result:

D393 =Boiling_water_q_nucleate(D384,D385,D387)

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 383 | | Data: | Fluid = | Water | | | |
| 384 | | Surface temp | T_s | 110 | C | | |
| 385 | | Sat. temp. | T_sat | 100.0 | C | | |
| 386 | | Radius of cyl. | Rad | 0.0005 | m | | |
| 387 | | Water-nickel combination | C_sf | 0.006 | From Table | | |
| 388 | | Length of wire | L | 0.15 | m | | |
| 389 | | Velocity | U_inf | 3.000 | m/s | | |
| 390 | | | | | | | |
| 391 | | Calculations: | | | | | |
| 392 | | | | | | | |
| 393 | | q_nucleate: | q_nucleate | 1392681.0834 | W/m^2 ... using VBA Function for Nucleate boiling | | |

Thus, $q_{boiling}$ = 1392681.08 W/m^2.

3. Next step is to find out the convection flux, $q_{conv}$. For cross flow over a cylinder, we use **Churchill and Bernstein equation:**

$$Nu_{cyl} = \frac{h \cdot D}{k} = 0.3 + \frac{0.62 \cdot Re^{\frac{1}{2}} \cdot Pr^{\frac{1}{3}}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}} \cdot \left[1 + \left(\frac{Re}{28200}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}} \quad \text{.....(9.90)}$$

Eqn. (9.90) is valid for $100 < Re < 10^7$, and Re.Pr > 0.2 and correlates very well all available data.

Fluid properties are evaluated at 'film temperature', $T_f = (T_s + T_a)/2$ = average of surface and free stream temperatures.

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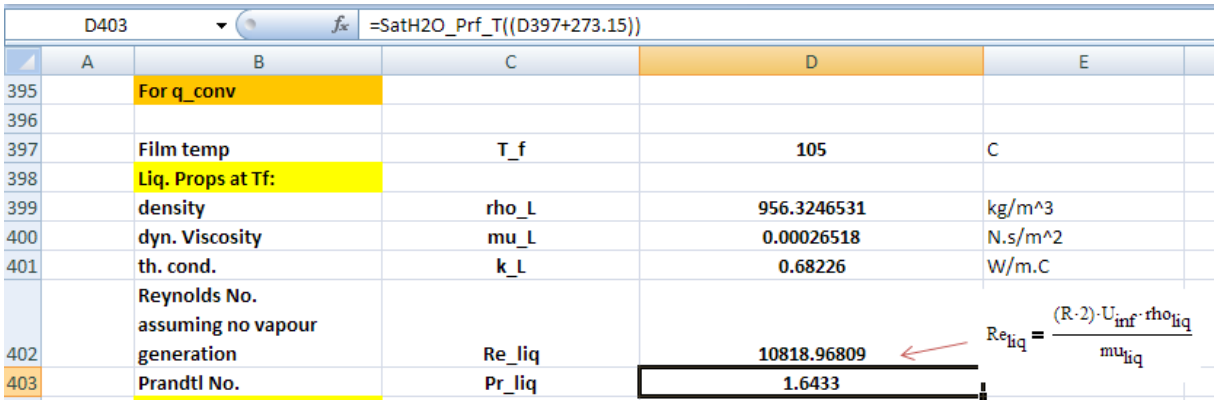
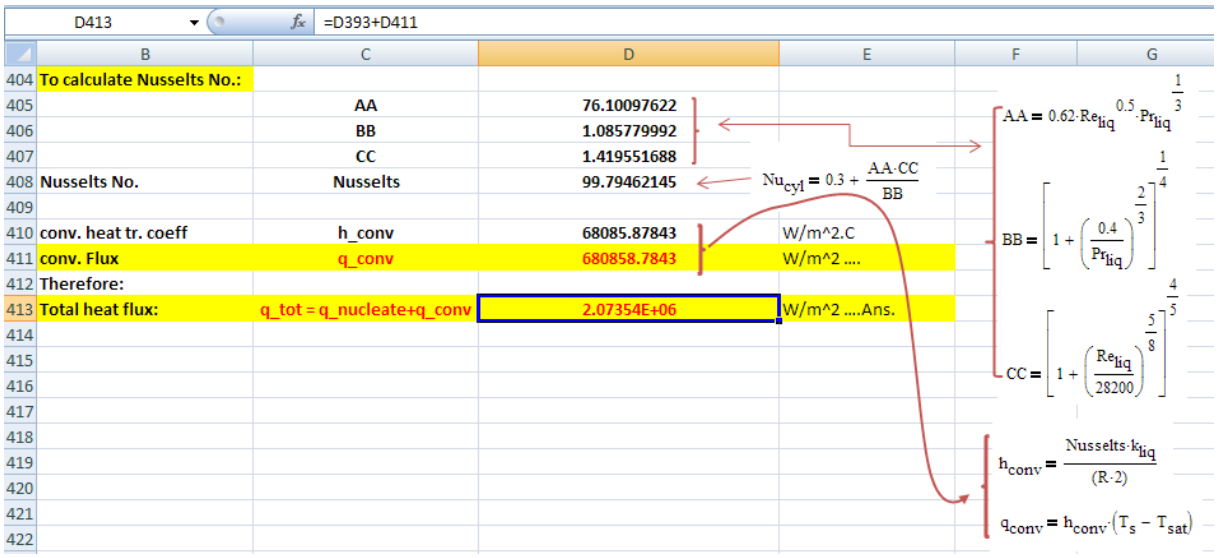
**We use properties of liquid at Tf, and assume zero vapour production:**

4. Get the Fluid properties by using the VBA Functions written earlier for Sat. water:




In the above worksheet, Reynolds No. is calculated using properties of liquid.

5. Next, calculate the Nusselts No. for cross flow over a cylinder. In the worksheet shown below, the eqn for Nusselts No. is calculated in parts, for clarity. From Nusselts no., calculate h_conv, and then q_conv, as shown:




**Thus:**

**Nucleate boiling flux, qboiling = 1392681.08 W/m^2.**

**Conv. heat flux = q_conv = 680858.78 W/m^2**

**Total heat flux = q_total = 2.07354E06 W/m^2 … Ans.**

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6. **What should be the flow velocity to make convective heat flux equal to the boiling heat flux?**

We see from the above calculations that nucleate boiling heat flux is independent of velocity.

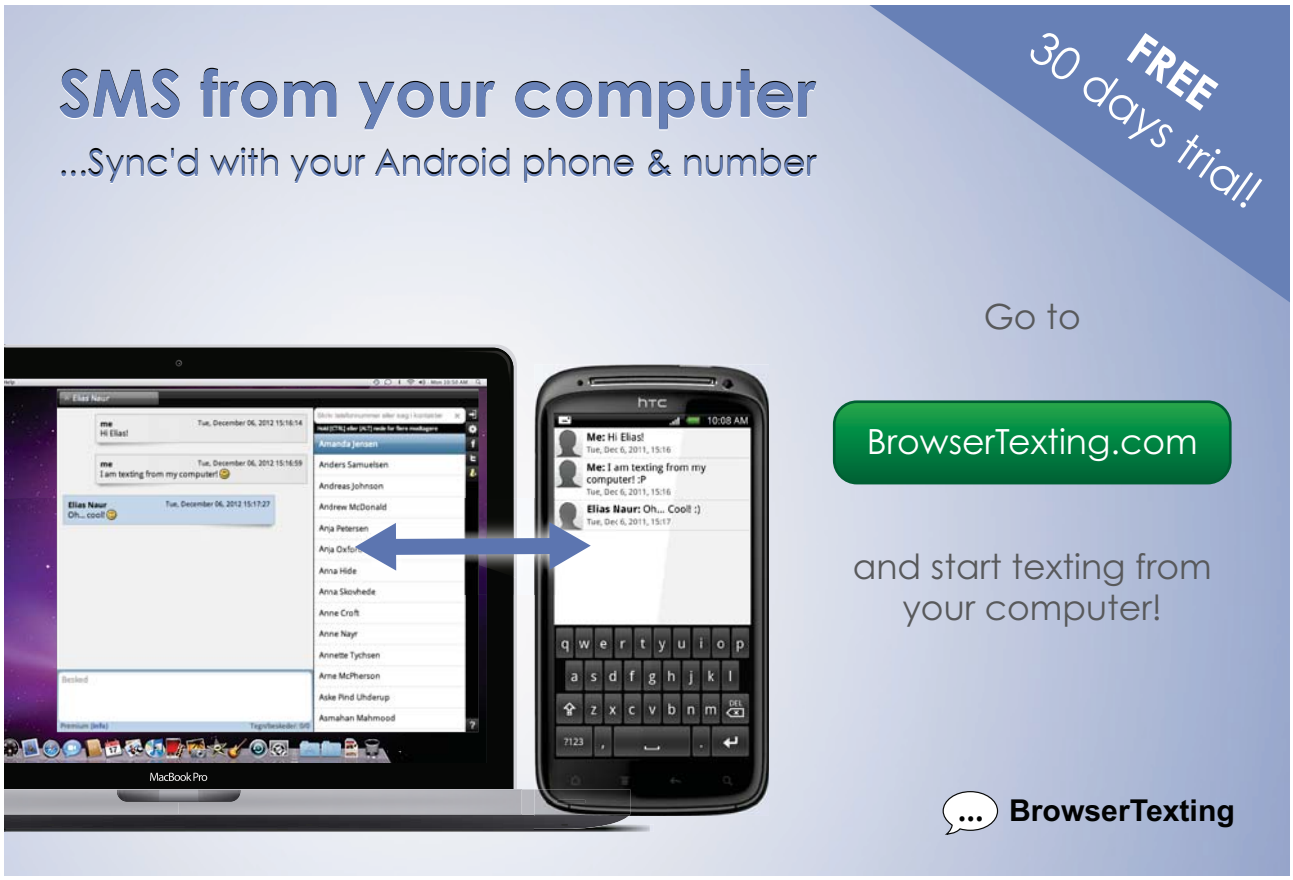
Convective heat flux is, of course, dependent on velocity.

To find the velocity which will make q_conv equal to q_boiling, we enter (q_conv – q_boiling) in cell D416.

D416 =D411-D393

| | B | C | D | E |
|---|---|---|---|---|
| 411 | conv. Flux | q_conv | 680858.7843 | W/m^2 .... |
| 412 | Therefore: | | | |
| 413 | Total heat flux: | q_tot = q_nucleate+q_conv | 2.07354E+06 | W/m^2 ....Ans. |
| 414 | | | | |
| 415 | | | | |
| 416 | Diff= | (q_conv - q_boiling) = | -711822.2991 | |
| 417 | | | | |

**And, apply Goal Seek to make cell D416 zero by changing cell D389 (i.e. value of velocity, U_inf).**



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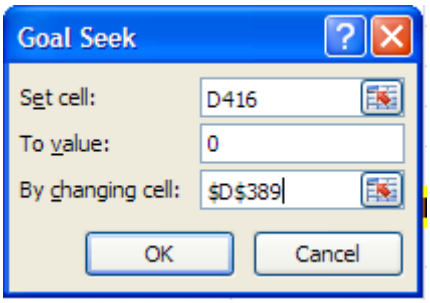
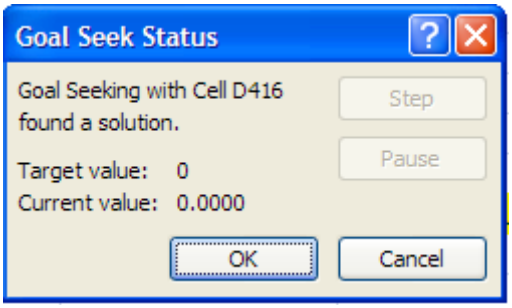
For procedure of Goal Seek, see problem 3.1.16.

We get:




Click OK. We get:




Again, click OK.

And, the result is:

**U_inf = 8.181 m/s…..Ans.**

==========

**Prob.3.1.21:** Estimate the flow velocity that would be necessary to produce a value of h for forced convection through a smooth, 6.5 mm dia brass tube comparable with that which could be obtained by pool boiling with $\Delta T_e$ = 15 C, and P = 6.9 bar, and water as the fluid. Take $T_{sat}$ = 164 C, and $h_{fg}$ = 2.068E06 J/kg at 6.9 bar.

**EXCEL Solution:**

First, find the Nucleate boiling flux for brass-water combination ($C_{sf}$ = 0.006) for the given T_s, T_sat.

From the flux, find out h_boiling.

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Then, assume a flow velocity (U_inf) and find h_conv using Dittus – Boelter eqn for Nusselts No. with the constant = 0.019 (instead of 0.023).

Next, apply Goal Seek to make both the h_conv and h_boiling equal, by changing velocity, U_inf.

Following are the steps:

1. Set up the worksheet, enter data:

F453

| | B | C | D | E |
|---|---|---|---|---|
| 429 | | | | |
| 430 | **Data:** | **Fluid =** | **Water** | |
| 431 | **Surface temp** | **T_s** | **179** | C |
| 432 | **Sat. temp.** | **T_sat** | **164.0** | C |
| 433 | **Radius of cyl.** | **Dia** | **0.0065** | m |
| 434 | **Water-brass combination** | **C_sf** | **0.006** | From Table |
| 435 | | | | |
| 436 | **Velocity .... Assumed** | **U_inf** | **3.000** | m/s |
| 437 | | | | |

2. First, calculate q_nucleate using the VBA Function for nucleate boiling. Then, h_boiling = q_nucleate / ΔT.

Now, get properties of water at bulk mean temp $T_f = T_{sat} + \Delta T/2 = 171.5$ C.

Following worksheet shows these calculations:

D443 =Boiling_water_q_nucleate(D431,D432,D434)

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 442 | | | | | | | |
| 443 | | q_nucleate: | q_nucleate | 18511560.8215 | W/m^2 ... using VBA Function for Nucleate boiling | | |
| 444 | | boiling. heat tr coeff | h_boiling | 1234104.055 | W/m^2.C | *h_boiling = q_nucleate / ΔT* | |
| 445 | | | | | | | |
| 446 | | Film temp | T_f | 171.5 | C | | |
| 447 | | Liq. Props at Tf: | | | | | |
| 448 | | density | rho_L | 895.8345931 | kg/m^3 | | |
| 449 | | dyn. Viscosity | mu_L | 0.000157583 | N.s/m^2 | | |
| 450 | | th. cond. | k_L | 0.6799075 | W/m.C | | |
| 451 | | Reynolds No. assuming no vapour generation | Re_liq | 110854.7876 | | *Re = D * U_inf * rho_liq / mu_liq* | |
| 452 | | Prandtl No. | Pr_liq | 1.019075 | | | |

The Function for q_nucleate, entered in cell D443 can be seen in the Formula bar.

For convection calculations, we are taking properties of liquid only, and assume zero vapour production.

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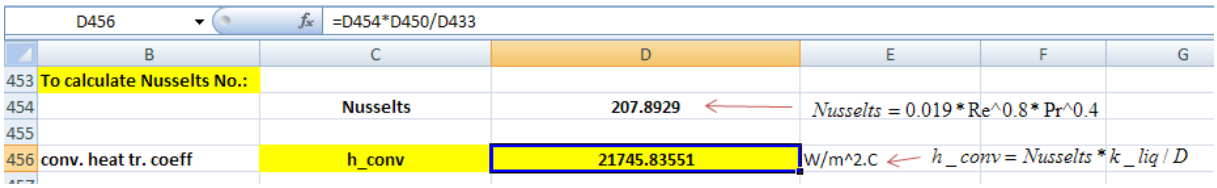
3. Now, find Reynolds No. = D * U_inf * rho / mu. Then, apply Dittus _ Boelter eqn (with constant = 0.019 instead of 0.023) to get Nusselts No. i.e.

$$Nusselts = 0.019 * \text{Re}^{0.8} * \text{Pr}^{0.4}$$

And, next, find h_conv from:

$$h\_conv = Nusselts * k\_liq / D$$

Following worksheet shows these calculations:



D456 =D454*D450/D433

| | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| 453 | To calculate Nusselts No.: | | | | | |
| 454 | | Nusselts | 207.8929 | ← Nusselts = 0.019 * Re^0.8 * Pr^0.4 | | |
| 455 | | | | | | |
| 456 | conv. heat tr. coeff | h_conv | 21745.83551 | W/m^2.C ← h_conv = Nusselts * k_liq / D | | |

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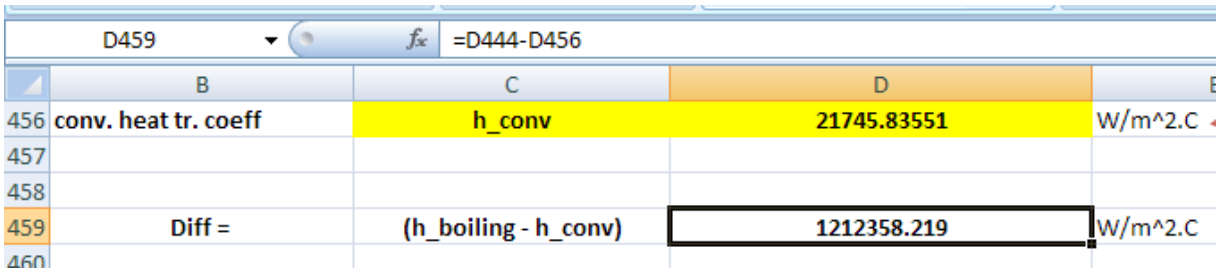
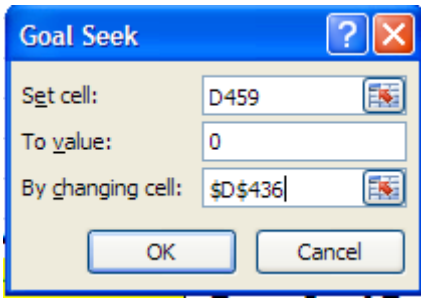
4. Now, all the above calculations were with the assumed value of 3 m/s for the velocity, U_inf. Now, enter (h_boiling – h_conv) in cell D459 and apply Goal Seek to make this cell equal to zero by changing cell D436 (i.e. value of U_inf).

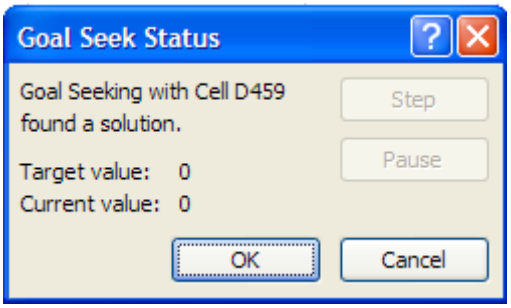



For procedure of Goal Seek, see problem 3.1.16.

We get:




Click OK. We get:




Again, click OK.

And, the result is:

**U_inf = 467.295 m/s…..Ans.**

i.e. quite a high value of velocity is required to get this heat flux in forced convection.

==========

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**Prob.3.1.22:** Water at 1 atm, with a mean velocity of 1.5 m/s and a mean temp of 95 C flows through a 15 mm dia brass tube, whose surface is at 110 C. Estimate the heat transfer rate per unit length. (Ref. 3)

**EXCEL Solution:**

Here, combine the separate effects of forced convection and nucleate boiling.

First, find the Nucleate boiling flux for brass-water combination ($C_{sf}$ = 0.006) for the given T_s, T_sat.

Then, find h_conv using Dittus-Boelter eqn for Nusselts No. with the constant = 0.019 (instead of 0.023), and then find out q_conv.

Following are the steps:

1. Set up the worksheet, enter data:

D472 | 1.5

| | B | C | D | E |
|---|---|---|---|---|
| 466 | **Data:** | **Fluid =** | **Water** | |
| 467 | **Surface temp** | **T_s** | **110** | C |
| 468 | **Sat. temp.** | **T_sat** | **100.0** | C |
| 469 | **Dia of cyl.** | **Dia** | **0.0150** | m |
| 470 | **Water-brass combination** | **C_sf** | **0.006** | From Table |
| 471 | | | | |
| 472 | **Velocity** | **U_inf** | **1.500** | m/s |
| 473 | | | | |

2. First, calculate q_nucleate using the VBA Function for nucleate boiling. Now, get properties of water at bulk mean temp $T_f$ = 95 C.

Following worksheet shows these calculations:

D479 | =Boiling_water_q_nucleate(D467,D468,D470)

| | B | C | D | E | F | G |
|---|---|---|---|---|---|---|
| 476 | | | | | | |
| 477 | **Calculations:** | | | | | |
| 478 | | | | | | |
| 479 | **q_nucleate:** | **q_nucleate** | **1392681.0834** | **W/m^2 ... using VBA Function for Nucleate boiling** | | |
| 480 | | | | | | |
| 481 | | | | | | |
| 482 | **Mean bulk temp** | **T_f** | **95** | C | | |
| 483 | **Liq. Props at Tf:** | | | | | |
| 484 | **density** | **rho_L** | **961.6401735** | kg/m^3 | | |
| 485 | **dyn. Viscosity** | **mu_L** | **0.00029529** | N.s/m^2 | | |
| 486 | **th. cond.** | **k_L** | **0.67826** | W/m.C | | |
| 487 | **Reynolds No. assuming no vapour generation** | **Re_liq** | **73273.40548** | Re = D * U _ inf* rho _ liq / mu _ liq | | |
| 488 | **Prandtl No.** | **Pr_liq** | **1.8407** | | | |

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The Function for q_nucleate, entered in cell D479 can be seen in the Formula bar.

For convection calculations, we are taking properties of liquid only, and assume zero vapour production.

1. Now, find Reynolds No. = D * U_inf * rho / mu. Then, apply Dittus _ Boelter eqn (with constant = 0.019 instead of 0.023) to get Nusselts No. i.e.

$$Nusselts = 0.019 * \text{Re}\text{^}0.8 * \text{Pr}\text{^}0.4$$

And, next, find h_conv from:

$$h\_conv = Nusselts * k\_liq / D$$

Nd, the convective heat flux from:

$$\boxed{q\_conv = h\_conv * (T\_s - T\_f)}$$

Then, Q_total *for unit length* is calculated as:

$$\boxed{Q\_tot = (q\_boiling + q\_conv) * (\pi * D)}$$

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Following worksheet shows these calculations:

D495 =(D479+D493)*(PI()*D469)

| | C | D | E | F | G | H |
|---|---|---|---|---|---|---|
| 488 | Pr_liq | 1.8407 | | | | |
| 489 | | | Nusselts = 0.019 * Re^0.8 * Pr^0.4 | | | |
| 490 | Nusselts | 189.1054 | h_conv = Nusselts * k_liq / D | | | |
| 491 | | | | | | |
| 492 | h_conv | 8550.841444 | W/m^2.C | | | |
| 493 | q_conv | 128262.6217 | W/m^2 | q_conv = h_conv * (T_s − T_f) | | |
| 494 | | | | | | |
| 495 | Q_tot | 71672.78355 | W/m....Ans. | Q_tot = (q_boiling + q_conv) * (π * D) | | |
| 496 | | | | | | |

**Thus: Total heat transfer from the tube = Q_tot = 71672.8 W/m …. Ans.**

==========

## 3.2 Condensation:

**Formulas used:**

**Film condensation and flow regimes: (Ref. 1)**

Consider film condensation of a vapour at saturation temperature $T_{sat}$ on the surface of a cooled vertical plate, maintained at a temperature $T_s$ (< $T_{sat}$.). See Fig. 11.7.

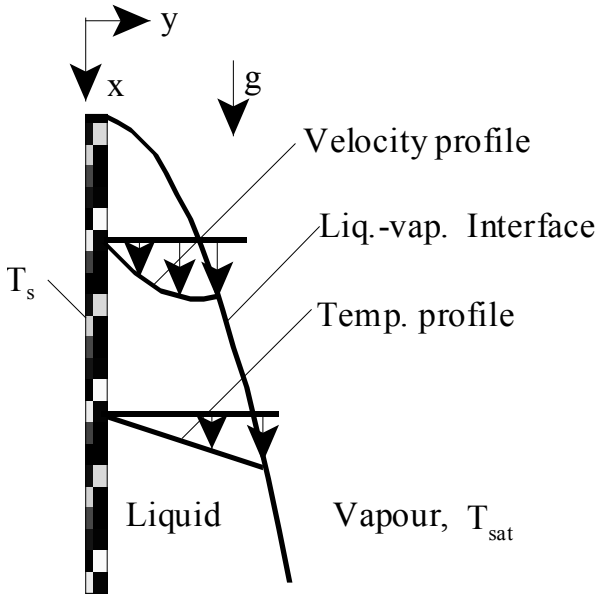


**Fig. 11.7** Film condensation on a vertical plate

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Vapour condenses on the top of the plate and flows down as a film. Thickness of the film (δ) is zero at the top of the plate (i.e. at x = 0 in the coordinate system shown) and increases as we travel down the plate (i.e. as x increases) due to additional condensation of vapour.

Initially, the liquid film flow is **laminar**; after some distance it will become **wavy** and later, it may even turn **turbulent**. *These different flow regimes are identified according to a **'film Reynolds number'**, defined as follows:*

$$Re_f = \frac{D_h \cdot \rho_L \cdot V_L}{\mu_L} = \frac{4 \cdot A_c \cdot \rho_L \cdot V_L}{P \cdot \mu_L} = \frac{4 \cdot \rho_L \cdot V_L \cdot \delta}{\mu_L} = \frac{4 \cdot m}{P \cdot \mu_L} \quad .....(11.32)$$

where

$D_h = 4\ A_c/P = 4.\delta$ = hydraulic dia. of condensate flow, m

P = wetted perimeter of condensate, m

$A_c = P.\ \delta$ = area of cross-section of flow at the lowest part of flow, $m^2$

$\rho_L$ = density of liquid, $kg/m^3$

$\mu_L$ = viscosity of liquid, kg/m.s

$V_L$ = average velocity of condensate at the lowest part of flow, m/s

$\rho_L\ A\ V_L = m$ = mass flow rate of condensate at the lowest part of flow, kg/s

For the common geometries of a vertical plate, vertical cylinder and a horizontal cylinder, **hydraulic diameter Dh is equal to 4 times the thickness of the condensate, δ, at the location where the hydraulic diameter is to be evaluated.**

Again, considering eqn. (11.32), for a vertical plate, wetted perimeter, P = B, the breadth; therefore, (m/P) is the mass flow rate per unit breadth. If we denote (m/P) by m', we can write for the vertical plate:

$$Re_f = \frac{4 \cdot m'}{\mu_L} \quad ....(11.32,a)$$

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Rohsenow (1956) suggested that sub-cooling of the liquid can be taken into account by replacing $h_{fg}$ by a **'modified latent heat of vapourization'**, $h'_{fg}$, defined as:

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s) \qquad .....(11.33)$$

where $C_{pL}$ is the sp. heat of liquid at the average film temperature.

Similarly, if a superheated vapour at a temperature, $T_v$, enters a condenser and condenses, the superheated vapour has to be cooled to $T_{sat}$ first, and then condensed at $T_{sat}$, and then sub-cooled to some temperature between $T_s$ and $T_{sat}$. Then. Modified latent heat of vapourization is:

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s) + C_{pV} \cdot (T_V - T_{sat}) \qquad .....(11.34)$$

where $C_{pV}$ is the sp. heat of vapour at the *average* temperature of $(T_V + T_{sat})/2$.

Then, rate of heat transfer in condensation becomes:

$$Q_{conden} = h \cdot A \cdot (T_{sat} - T_s) = m \cdot h'_{fg} \qquad ....(11.35)$$

where A is the surface area on which condensation occurs.

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Then, from eqn. (11.35) and (11.32), we can write:

$$Re_f = \frac{4 \cdot Q_{conden}}{P \cdot \mu_L \cdot h'_{fg}} = \frac{4 \cdot A \cdot h \cdot (T_{sat} - T_s)}{P \cdot \mu_L \cdot h'_{fg}} \quad \ldots.(11.36)$$

When either $Q_{conden}$ or h is known, it is convenient to use eqn. (11.36) to determine $Re_f$.

**Now, different flow regimes are identified according to the value of Ref as follows:**

$Re_f \leq 30$ ….Liquid film is smooth and wave-free, i.e. **fully laminar**.

$450 < Re_f < 1800$ ….Liquid film has ripples or waves and the flow is **wavy-laminar**.

$Re_f > 1800$ ….Liquid film is **fully turbulent**.

Heat transfer correlations vary depending upon the flow regime.

**Nusselt's theory for Laminar film condensation on Vertical Plates:**

Velocity profile:

$$u(y) = \frac{g \cdot (\rho_L - \rho_V) \cdot \left(\delta \cdot y - \frac{y^2}{2}\right)}{\mu_L}$$

i.e. $$u(y) = \frac{g \cdot (\rho_L - \rho_V) \cdot \delta^2}{\mu_L} \cdot \left[\frac{y}{\delta} - \frac{1}{2} \cdot \left(\frac{y}{\delta}\right)^2\right] \quad \ldots\ldots(11.37)$$

And, the mean flow velocity of the liquid at a section is given by:

$$u_m = \frac{g \cdot (\rho_L - \rho_V) \cdot \delta^2}{3 \cdot \mu_L} \quad \ldots\ldots(11.38)$$

Mass flow rate of condensate through any x-position is given by:

$$m = \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot g \cdot b \cdot \delta^3}{3 \cdot \mu_L} \quad \ldots\ldots(11.39)$$

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The liquid film thickness as a function of position x is given by:

$$\delta(x)=\left[\frac{4\cdot k_L\cdot\mu_L\cdot\left(T_{sat}-T_s\right)\cdot x}{\rho_L\cdot\left(\rho_L-\rho_V\right)\cdot g\cdot h_{fg}}\right]^{\frac{1}{4}} \quad .....(11.43)$$

Local heat transfer coeff. is given by:

$$h_x=\frac{k}{\delta} \quad ....(11.44)$$

Substituting the value of δ from eqn. (11.43) in eqn. (11.44):

$$h_x=\left[\frac{\rho_L\cdot\left(\rho_L-\rho_V\right)\cdot k_L^{\,3}\cdot g\cdot h_{fg}}{4\cdot\mu_L\cdot x\cdot\left(T_{sat}-T_s\right)}\right]^{\frac{1}{4}} \quad .....(11.45)$$

At x = L, i.e. at the lower end of the plate, local heat transfer coeff. is:

$$h_L=\left[\frac{\rho_L\cdot\left(\rho_L-\rho_V\right)\cdot k_L^{\,3}\cdot g\cdot h_{fg}}{4\cdot\mu_L\cdot L\cdot\left(T_{sat}-T_s\right)}\right]^{\frac{1}{4}} \quad .....(11.46)$$

**Average value of heat transfer coeff. over the entire height of the plate:**

$$h_{avg}=\frac{1}{L}\cdot\int_0^L h_x\,dx$$

We get:

$$h_{avg}=\frac{4}{3}\cdot h_L \quad ....(11.47)$$

In the above, $h_L$ is the local heat transfer coeff. at x = L, i.e. at the lower end of the plate.

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**We have, for average heat transfer coeff. for laminar film condensation on a vertical plate:**

$$h_{avg} = 0.943 \cdot \left[ \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot L \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad W/(m^2.C)...\text{for } 0 < Re_f < 30.....(11.49)$$

where

$$h'_{fg} = h_{fg} + 0.68 \cdot C_{pL} \cdot (T_{sat} - T_s)$$

**In the above eqn. all the liquid properties should be evaluated at the film temperature,**

**Tf = (Tsat + Ts)/2 and hfg and ρV should be evaluated at Tsat.**

---

Now, let us define a dimensionless number called **'Condensation number'**, (Co) [or, 'modified Nusselt number'] as follows:

$$Co = \frac{h_{avg}}{k_L} \cdot \left[ \frac{\mu_L^2}{\rho_L \cdot (\rho_L - \rho_V) \cdot g} \right]^{\frac{1}{3}} \quad .....(11.50, a)$$

Since , $\rho_L >> \rho_V$, condensation number can be simplified as:

$$Co = \frac{h_{avg}}{k_L} \cdot \left( \frac{\mu_L^2}{\rho_L^2 \cdot g} \right)^{\frac{1}{3}} = \frac{h_{avg}}{k_L} \cdot \left( \frac{\nu_L^2}{g} \right)^{\frac{1}{3}} \quad ....(11.50, b)$$

Then, Rohsenow (1985) has shown that above derived relation for heat transfer coeff. for condensation on a vertical plate for the laminar regimes of condensate flow, can be recast as follows:

a) **Laminar flow, (Ref ≤ 30):**

$$Co = 1.47 \cdot Re_f^{\frac{-1}{3}} \quad ..laminar....(11.51)$$

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b) **In the laminar – wavy region, (30 < Ref < 1800):**

Kutatelazde recommends following correlation:

$$Co = \frac{Re_f}{1.08 \cdot Re_f^{1.22} - 5.2} \quad \text{....laminar-wavy.....(11.52)}$$

c) **For turbulent region, (Ref > 1800):**

Labuntsov recommends following correlation for turbulent film condensation:

$$Co = \frac{Re_f}{8750 + 58 \cdot \left(Re_f^{0.75} - 253\right) \cdot Pr_L^{-0.5}} \quad \text{...turb.....(11.53)}$$

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Eqns. (11.51), (11.52) and (11.53) are depicted graphically in Fig. (11.9) below:

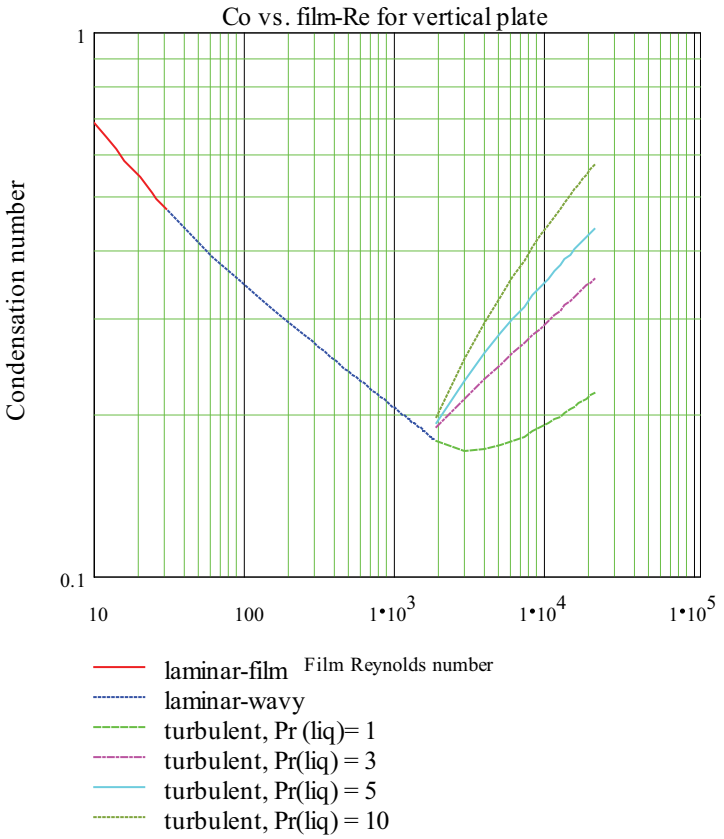


**Fig. 11.9** Condensation number vs. film Reynolds number for a vertical plate

Above correlations for condensation on a vertical plate are applicable to condensation inside or outside vertical tubes also, if the tube diameter is not too small.

**Calculation formulas** for all the three regions of film condensation on a vertical plate (or cylinder) are given below (from Ref. 2, Cengel). Here, $h_{vert}$ is the average heat transfer coeff over the entire height (L) of the vertical plate.

$delta_L$ is the thickness of the film at the bottom of the plate, i.e. at x = L.

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**For Laminar film: (i.e. 0 < Re <= 30):**

$$delta_L = \left[ \frac{4 \cdot mu_L \cdot k_L \cdot (T_{sat} - T_s) \cdot L}{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime}} \right]^{\frac{1}{4}}$$

$$Re = \frac{4 \cdot g \cdot rho_L \cdot (rho_L - rho_V) \cdot delta_L^{\,3}}{3 \cdot mu_L^{\,2}}$$

$$h_{vert} = 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} \quad \text{if } 0 < Re \le 30$$

---

**For Laminar-wavy film: (i.e. 30 < Re <= 1800):**

$$h_{vert} = \frac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$$

$$Re_f = \left[ 4.81 + \frac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} \right]^{0.82}$$

---

**For turbulent film: (i.e. Re > 1800):**

$$h_{vert} = \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{\,-0.5} \cdot \left( Re^{0.75} - 253 \right)} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$$

$$Re_f = \left[ \frac{0.069 \cdot L \cdot k_L \cdot Pr_L^{\,0.5} \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} - 151 \cdot Pr_L^{\,0.5} + 253 \right]^{\frac{4}{3}}$$

---

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**Film condensation on inclined plates, vertical tubes, horizontal tubes and spheres, and horizontal tube banks:**

If the plate is inclined at an angle of θ to the vertical, (θ ≤ 60 deg.), replacing g by g.cos(θ) in eqn. (11.49) gives satisfactory results for laminar condensation on the upper surface of the inclined plate. i.e.

$$h_{inclined}=0.943\cdot\left[\frac{\rho_L\cdot\left(\rho_L-\rho_V\right)\cdot k_L^{3}\cdot g\cdot\cos(\theta)\cdot h'_{fg}}{\mu_L\cdot L\cdot\left(T_{sat}-T_s\right)}\right]^{\frac{1}{4}} \quad W/(m^2.C)...\text{for } 0 < Re_f < 30.....(11.55)$$

We can also write:

$$h_{inclined}=h_{vert}\cdot(\cos(\theta))^{\frac{1}{4}} \quad ....\text{laminar}.....(11.56)$$

**Vertical tubes:**

Eqn. (11.49) for laminar condensation on vertical plates can also be used to determine heat transfer coeff. for laminar condensation on the outer or inner surface of a vertical tube, if the tube diameter is large compared to the thickness of the liquid film i.e.

if D >> δ.

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**Horizontal tubes and spheres:**

**Horizontal tube-laminar film condensation:**

For laminar film condensation on horizontal tubes and spheres, Nusselt type of analysis gives relations similar to eqn. (11.49), except that L is replaced by diameter D and the value of the numerical constant is different. We get:

$$h_{horiz} = 0.729 \left[ \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot D \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad W/(m^2.C)...for\ 0 < Re_f < 30.....(11.57)$$

**Horizontal tube-forced convection condensation:**

Eqn. (11.57) is for the case of a quiescent vapour condensing on a horizonal tube. However, for condensers used in practice, a vapour may be forced through a condenser while being condensed. For the case of a cylinder of diameter D exposed to cross flow of a vapour with a free stream velocity of U, following correlation due to Shekriladze and Gomelauri (1966), may be applied:

$$\frac{h_{horiz} \cdot D}{k} = 0.64 \cdot Re_D^{\frac{1}{2}} \cdot \left[ 1 + \left[ 1 + \frac{1.69 \cdot g \cdot h'_{fg} \cdot \mu_L \cdot D}{U^2 \cdot k_L \cdot (T_{sat} - T_s)} \right]^{\frac{1}{2}} \right]^{\frac{1}{2}} \quad .. for\ Re_D < 10^6....(11.57,a)$$

where $Re_D = \frac{\rho_L \cdot U \cdot D}{\mu_L}$

**Sphere-laminar film condensation:**

$$h_{sphere} = 0.815 \left[ \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot D \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad W/(m^2.C)...for\ 0 < Re_f < 30.....(11.58)$$

It is interesting **to compare the laminar condensation on vertical and horizontal tubes.** From eqns. (11.49) and (11.57), we can write:

$$\frac{h_{vert}}{h_{horiz}} = \frac{0.943}{0.729} \cdot \left( \frac{D}{L} \right)^{\frac{1}{4}} = 1.294 \left( \frac{D}{L} \right)^{\frac{1}{4}} \quad ....(11.59)$$

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For $h_{vert}$ to be equal to $h_{horiz}$, we should have:

$$L = (1.294)^4 \cdot D$$

i.e.

$$L = 2.8 \cdot D$$

i.e. for L > 2.8.D, heat transfer coeff. will be higher for a horizontal tube. It is a fact that most of the tubes used in practice have lengths such that L > 2.8.D. Therefore, tubes used in a steam condenser are generally arranged in a horizontal orientation.

**Horizontal tube banks:**

Average heat transfer coeff. for film condensation on a vertical tier containing N tubes is obtained by substituting (N.D) in place of D in eqn. (11.57) for a single horizontal tube. i.e.

$$h_{horiz\_Ntubes} = 0.729 \cdot \left[ \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot (N \cdot D) \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad W/(m^2.C)...\text{for } 0 < Re_f < 30.....(11.60)$$

Clearly, this is related to the value of heat transfer coeff. for a single horizontal tube as follows:

$$h_{horiz\_Ntubes} = \frac{1}{N^{\frac{1}{4}}} \cdot h_{horiz\_1tube} \quad .....(11.61)$$

Chen (1961) has suggested the following modified form of eqn.(11.57) for condensation on a vertical tube bank, to take into account the condensation occurring on the sub-cooled film between two adjacent tubes:

$$h_{horiz\_Ntubes} = 0.725 \cdot \left[ \frac{\rho_L \cdot (\rho_L - \rho_V) \cdot k_L^3 \cdot g \cdot h'_{fg}}{\mu_L \cdot (N \cdot D) \cdot (T_{sat} - T_s)} \right]^{\frac{1}{4}} \cdot \left[ 1 + 0.2 \cdot \frac{C_{pL} \cdot (T_{sat} - T_s) \cdot (N-1)}{h_{fg}} \right] \quad ...(11.61)$$

**Note that the second square brackets on the RHS, is a correction factor to eqn. (11.60); also note that term inside this square bracket is $h_{fg}$ and not $h'_{fg}$. Eqn. (11.61) is valid for:**

$$\frac{C_{pL} \cdot (T_{sat} - T_s)}{h_{fg}} \leq 2 \quad \text{and,} \quad Pr_L \geq 1$$

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And,

$$\frac{C_{pL}\cdot\left(T_{sat}-T_s\right)}{h_{fg}}=Ja=Jacob\_number$$

==========

**Prob.3.2.1.** Saturated steam at atmospheric pressure condenses on a vertical plate (size: 30 cm × 30 cm) maintained at 60 C. Determine heat transfer rate and the mass of steam condensed per hour.

(b) If the plate is tilted at an angle of 30 deg. to the vertical, what is the value of condensation rate?

**Mathcad Solution:**

In Mathcad we have already written Functions for properties of Sat. water and also for Steam, as functions of temperature.

So, now, in the same worksheet, **let us write Functions for Film condensation of water (i.e. steam) on various geometries, using the equations given above.**

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**Mathcad Function to find h_vert etc. for Film condensation of steam on a vertical plate:**

**Input:** Ts, Tsat (C), L, b (m)

**Output:** delta_L, h (W/m^2.C), Re_film, Q (W), m_cond (kg/s) in a Matrix

**Note:** Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

Following are the steps:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 10: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written

Line 11: hfg_prime is calculated

Line 12: value of g is entered

Line 13: delta_L, the film thickness at a distance L from top, is calculated

Line 14: Re, the 'film Reynold's No.' is calculated

Line 15: If Re < 30, it is pure laminar film condensation, and h_vert (i.e. average heat tr. coeff.) is calculated as per the formula shown

Line 16, 17, 18: If 30 < Re < =1800, it is 'laminar-wavy' film, and now, the h_vert and the new Re_f are calculated as per the calculation formulas

Line 19, 20, 21: If Re > 1800, it is 'turbulent' film, and now, h_vert and the new Re_f are calculated again as per the calculation formulas

Line 22: heat transfer, Q is calculated as: Q = h_vert * (L * b ) * (Tsat – Ts)

Line 23: mass of steam condensed is calculated

Line 24: AA is defined as a Matrix of 2 rows and 5 columns, first row being the column headings and the second row giving values of delta_L, h_vert, Re_f, Q and m_condensed.

Line 25: returns this Matrix as the output of the Function.

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See the Function below:

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) :=$$

return "Ts must be less than Tsat ! " if $T_s - T_{sat} \geq 0$

$T_f \leftarrow \dfrac{T_s + T_{sat}}{2}$

$rho_L \leftarrow \dfrac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)}$

$rho_V \leftarrow \dfrac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$

$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$

$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15)$

$k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15)$

$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15)$

$Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_f + 273.15)$

$\nu_L \leftarrow \dfrac{mu_L}{rho_L}$

$h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s)$

$g \leftarrow 9.81$

$delta_L \leftarrow \left[ \dfrac{4 \cdot mu_L \cdot k_L \cdot (T_{sat} - T_s) \cdot L}{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime}} \right]^{\frac{1}{4}}$

$Re \leftarrow \dfrac{4 \cdot g \cdot rho_L \cdot (rho_L - rho_V) \cdot delta_L^{\,3}}{3 \cdot mu_L^{\,2}}$

$h_{vert} \leftarrow 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left( \dfrac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$ if $0 < Re \leq 30$

if $30 < Re \leq 1800$

$h_{vert} \leftarrow \dfrac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left( \dfrac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$

$Re_f \leftarrow \left[ 4.81 + \dfrac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \dfrac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} \right]^{0.82}$

if $Re > 1800$

$h_{vert} \leftarrow \dfrac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{\,-0.5} \cdot (Re^{0.75} - 253)} \cdot \left( \dfrac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$

$Re_f \leftarrow \left[ \dfrac{0.069 \cdot L \cdot k_L \cdot Pr_L^{\,0.5} \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \dfrac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} - 151 \cdot Pr_L^{\,0.5} + 253 \right]^{\frac{4}{3}}$

$Q \leftarrow h_{vert} \cdot (L \cdot b) \cdot (T_{sat} - T_s)$

$m_{condensed} \leftarrow \dfrac{Q}{h_{fg\_prime}}$

$AA \leftarrow \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ delta_L & h_{vert} & Re_f & Q & m_{condensed} \end{pmatrix}$

AA

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Now, let us use this Function to get results for the above problem:

**Data:**

$T_s := 60 \quad T_{sat} := 100 \quad L := 0.3 \quad b := 0.3$

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.506 \times 10^{-4} & 7.28 \times 10^{3} & 404.868 & 2.621 \times 10^{4} & 0.011 \end{pmatrix}$$

Immediately, we see that:

**heat transfer rate, Q = 26210 W … Ans.**

**steam condensed = 0.011 kg/s = 39.6 kg/h … Ans.**

In addition, note the value of thickness of film at the bottom of the plate (i.e. at x = L), and h_vert and Re_f. Since Re_f is between 30 and 1800, it is 'laminar-wavy' region.

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**(b) If the plate is tilted at an angle of 30 deg. to the vertical, what is the value of condensation rate?**

Now, eqns for vertical plate are used, but h_inclined = h_vert * (cos (θ))^(1/4) where θ (deg.) is the inclination of the plate to the vertical.

Following is the Mathcad Function for an Inclined plate, inclined at θ degrees to vertical:

**Mathcad Function to find h_vert for Film condensation of steam on an Inclined plate, inclined at theta deg to the vertical:**

**Input:** Ts, Tsat (C), L, b (m), theta (deg.)

**Output:** h_film (W/m^2.C)

**Note:** Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

$$\text{FilmCondensation\_Steam\_InclinedVPlate\_h}(T_s, T_{sat}, L, b, \text{theta}) := \left|\begin{array}{l} \text{return "Ts must be less than Tsat ! "} \quad \text{if } T_s - T_{sat} \geq 0 \\ AA \leftarrow \text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) \\ h_{vert} \leftarrow AA_{1,1} \\ \text{theta\_rad} \leftarrow \frac{\text{theta} \cdot \pi}{180} \\ h_{inclined} \leftarrow h_{vert} \cdot (\cos(\text{theta\_rad}))^{\frac{1}{4}} \\ h_{inclined} \end{array}\right.$$

In the above program, we have:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Mathcad Function wrotten above for a vertical plate is invoked, and the resulting Matrix is assigned to AA

Line 3: h_vert is reads off from the Matrix. Remember that result of the Function is a 2 × 5 Matrix. In Mathcad, by default, rows and columns are *numbered starting from zero* (not 1 , which is usual). So, note that ***h_vet is the element AA is the element in the first row, first column as per this notation.***

Line 4: theta is converted to radians since in Mathcad arguments to trigonometric functions should be in Radians.

Line 5: h_inclined is calculated

Line 6: value of h_inclined is returned as the output of this Mathcad Function

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**Now, applying the above Function for this problem:**

**When the plate is inclined at 30 deg. to vertical:**

$T_s := 60\ C \quad T_{sat} := 100\ C \quad L := 0.3\ m \quad b := 0.3\ m \quad theta := 30\ deg.$

$FilmCondensation\_Steam\_InclinedVPlate\_h(T_s, T_{sat}, L, b, theta) = 7.023 \times 10^3$ W/m^2.C

Therefore: $Q := 7023 \cdot (0.3 \cdot 0.3) \cdot (T_{sat} - T_s)$

i.e. $Q = 2.528 \times 10^4$ W

and, $m_{cond} := \frac{Q}{2257 \cdot 10^3}$

i.e. $m_{cond} = 0.0112$ kg/s

==========

**Prob.3.2.2.** Saturated steam at 80 C condenses as a film on a vertical plate maintained at 70 C. Calculate the average heat transfer coeff. and the rate of condensation. [VTU – M.Tech. – June/July 2009]

**Mathcad Solution:**

Apply the Function written above directly:

$T_s := 70\ C \quad T_{sat} := 80\ C \quad L := 1\ m \quad b := 1\ m$

$$FilmCondensation\_Steam\_VertPlate(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.463 \times 10^{-4} & 7.305 \times 10^3 & 323.82 & 7.305 \times 10^4 & 0.031 \end{pmatrix}$$

**Note:** Since the size of plate is not given, we have assumed it to be 1 m × 1 m.

**Thus, h_avg = 7305 W/m^2.C, and m_cond = 0.031 kg/s per m^2 area …. Ans.**

==========

**Prob.3.2.3.** A vertical plate, 500 mm high and 200 mm wide is to be used to condense sat. steam at 1 atm. (a) At what surface temp must the plate be maintained to achieve a condensation rate of 25 kg/h?

(b) compute and plot the surface temp as a function of condensation rate for 15 < m_cond < 50 kg/h

**(Ref: 3)**

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**Mathcad Solution:**

We shall use the Mathcad Function already written for a vertical plate, and apply 'Solve block' of Mathcad to find Ts to get the desired condensation rate:

Following is the worksheet:

First, assume a value for Ts and do the calculations using the Mathcad Function written earlier for a vertical plate:

**Data:**

$T_s := 60$ C.... assumed value

$T_{sat} := 100$ C $\quad L := 0.5$ m $\quad b := 0.2$ m

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 1.711 \times 10^{-4} & 6.682 \times 10^{3} & 614.859 & 2.673 \times 10^{4} & 0.011 \end{pmatrix}$$

Now, m_cond is the element (1,4) in the Matrix above. (Remember: numbering of rows and columns starts from zero in Mathcad).

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So, let us apply the 'Solve Block' of Mathcad to get the value of Ts such that m_cond will be 25 kg/h = (25/3600) kg/s:

$m_{cond} := 25$ kg/h .... required as per data

Given

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b)_{1,4} = \frac{m_{cond}}{3600}$$

$$Ts(m_{cond}) := \text{Find}(T_s)$$

Note that we have written the result of Solve Block, viz. Ts as a function of M_cond so that we can easily draw the plot of Ts vs m_cond later:

We get:

Therefore:

$Ts(m_{cond}) = 79.36$ **C....Ans.**

**i.e. Value of surface temp required to get a condensation rate of 25 kg/h is 79.36 deg. C … Ans.**

**Now, plot Ts vs m_cond:**

$m_{cond} := 15, 20 .. 50$ ....define m_cond as a range variable from 15 to 50 kg/h

| $m_{cond}$ = | $Ts(m_{cond})$ = |
|---|---|
| 15 | 89.278 |
| 20 | 84.55 |
| 25 | 79.36 |
| 30 | 73.71 |
| 35 | 67.555 |
| 40 | 60.825 |
| 45 | 53.408 |
| 50 | 45.424 |

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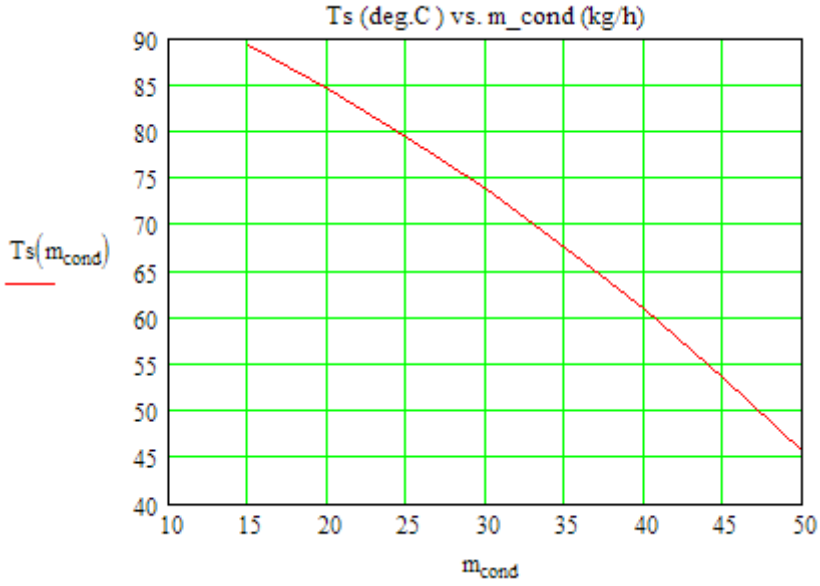


==========

**Prob.3.2.4.** A vertical plate, 2.5 m high, maintained at a uniform temp of 54 C, is exposed to sat. steam at atm. pressure.

a) Estimate the condensation and heat transfer rates per unit width of the plate
b) If the plate height were halved, would turbulent flow still exist?
c) For 54 < Ts < 90 C, plot the condensation rate as a function of plate temp for the two plate heights of parts (a) and (b). (Ref: 3)

**Mathcad Solution:**

We shall use the Mathcad Function already written for a vertical plate.

Following is the worksheet:

**Data:**

$T_s := 54$ C....

$T_{sat} := 100$ C  $L := 2.5$ m  $b := 1$ m

FilmCondensation_Steam_VertPlate$(T_s, T_{sat}, 2.5, b)$ =

| "delta L(m)" | "h avg(W/m^2.C)" | "Re f" | "Q (W)" | "m cond (kg/s)" |
|---|---|---|---|---|
| $2.665 \times 10^{-4}$ | $4.925 \times 10^{3}$ | $2.433 \times 10^{3}$ | $5.664 \times 10^{5}$ | 0.237 |

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**We observe that:**

**Re_f = 2433 > 1800…Therefore, it is turb. flow.**

**Heat transfer, Q = 5.664E05 W ….Ans.**

**Condensation rate, m_cond = 0.237 kg/s …. Ans.**

---

**(b) When the vertical height is halved, i.e. L = 1.25 m, we have:**

$$\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, 1.25, b) = \left(\begin{array}{|ccccc|} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 2.241 \times 10^{-4} & 5.524 \times 10^{3} & 1.379 \times 10^{3} & 3.176 \times 10^{5} & 0.133 \end{array}\right)$$

**We see that:**

**Re_f = 1379 . i.e. 30 < Re_f < 1800 … Therefore, it is *not turb. film*, but *wavy laminar film*…..Ans.**

---

**(c) Plot the condensation rate as a function of plate temp, for plate heights L = 2.5 m and L = 1.25 m:**

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**For L = 2.5 m:**

Note that in the output of the Mathcad Function, m_cond is element (1,4) i.e. element in the first row, 4th column. *Remember that numbering of rows and columns starts from zero in Mathcad, by default.*

$T_s := 54, 60 .. 90$ C .... define a range variable for Ts

For this range of Ts, m_cond is given as:

| $T_s =$ | $\text{FilmCondensation\_Steam\_VertPlate}(T_s, T_{sat}, L, b)_{1,4}$ |
|---|---|
| 54 | 0.262 |
| 60 | 0.231 |
| 66 | 0.2 |
| 72 | 0.167 |
| 78 | 0.139 |
| 84 | 0.109 |
| 90 | 0.075 |

**Now, for L = 1.25 m:**

Take the same variation of Ts as earlier, i.e.

$T_{s2} := 54, 60 .. 90$ C .... define a range variable for Ts

And, the corresponding values of m_cond are:

| $T_{s2} =$ | $\text{FilmCondensation\_Steam\_VertPlate}(T_{s2}, T_{sat}, 1.25, b)_{1,4}$ |
|---|---|
| 54 | 0.133 |
| 60 | 0.121 |
| 66 | 0.108 |
| 72 | 0.094 |
| 78 | 0.078 |
| 84 | 0.061 |
| 90 | 0.042 |

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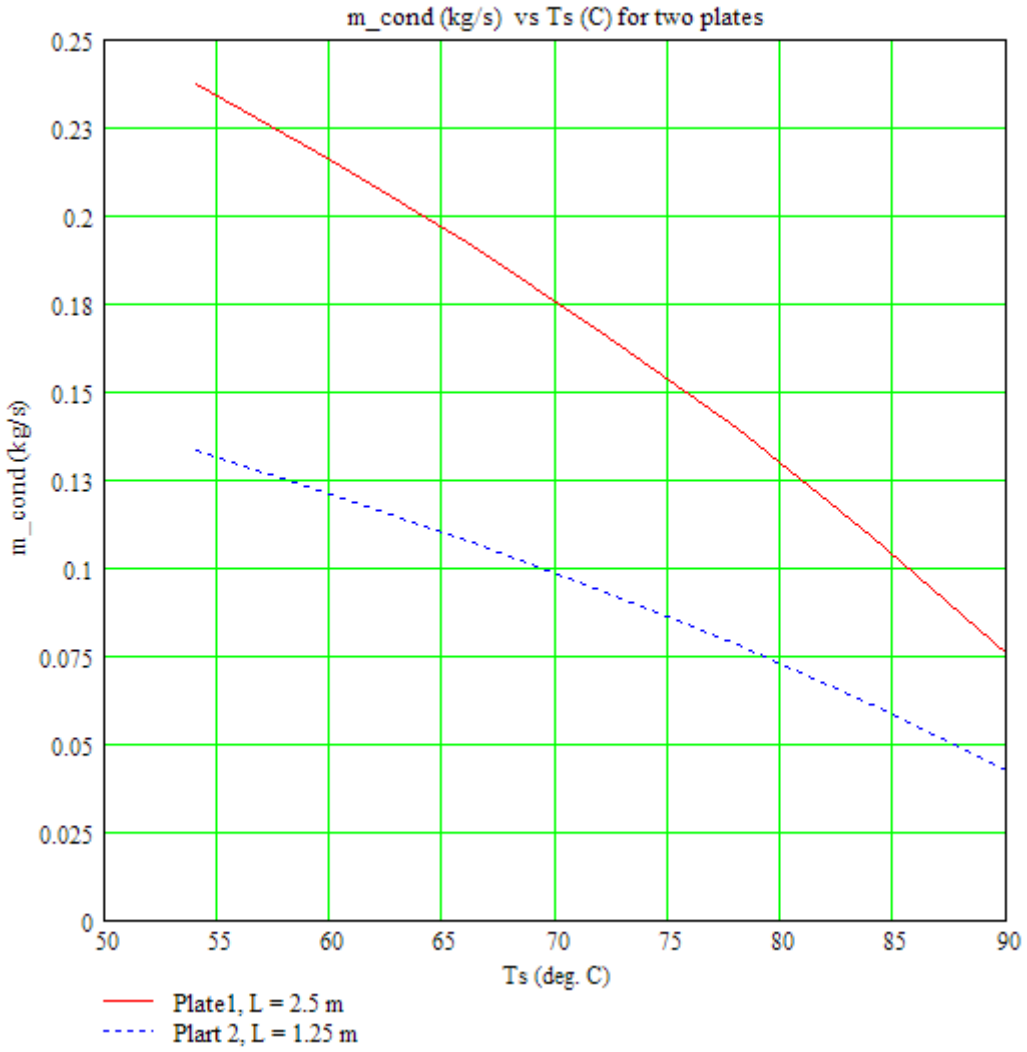
**Now, plot the variation of m_cond against Ts for both the plates, on the same graph:**




==========

**Mathcad Function to find h_vert etc. for Film condensation of steam on a vertical cylinder:**

**Input:** Ts, Tsat (C), L, D (m)

**Output:** delta_L, h (W/m^2.C), Re_film, Q (W), m_cond (kg/s) in a Matrix

When D >> delta_L, *eqns for vertical plate can be used for vertical cylinder too.*

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**Let us write a Mathcad Function to calculate various parameters for this case.**

FilmCondensation_Steam_VertCyl($T_s, T_{sat}, L, D$) :=

return "Ts must be less than Tsat ! " if $T_s - T_{sat} \geq 0$

$T_f \leftarrow \frac{T_s + T_{sat}}{2}$

$rho_L \leftarrow \frac{1}{vf\_H2O(TempK, H2Ov\_f, T_f + 273.15)}$

$rho_V \leftarrow \frac{1}{vg\_H2O(TempK, H2Ov\_g, T_{sat} + 273.15)}$

$h_{fg} \leftarrow h\_fg\_H2O(TempK, H2Oh\_fg, T_{sat} + 273.15)$

$mu_L \leftarrow mu\_f\_H2O(TempK, H2Omu\_f, T_f + 273.15)$

$k_L \leftarrow k\_f\_H2O(TempK, H2Ok\_f, T_f + 273.15)$

$cp_L \leftarrow cp\_f\_H2O(TempK, H2Ocp\_f, T_f + 273.15)$

$Pr_L \leftarrow Pr\_f\_H2O(TempK, H2OPr\_f, T_f + 273.15)$

$\nu_L \leftarrow \frac{mu_L}{rho_L}$

$h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot cp_L \cdot (T_{sat} - T_s)$

$g \leftarrow 9.81$

$delta_L \leftarrow \left[ \frac{4 \cdot mu_L \cdot k_L \cdot (T_{sat} - T_s) \cdot L}{g \cdot rho_L \cdot (rho_L - rho_V) \cdot h_{fg\_prime}} \right]^{\frac{1}{4}}$

$Re \leftarrow \frac{4 \cdot g \cdot rho_L \cdot (rho_L - rho_V) \cdot delta_L^{\,3}}{3 \cdot mu_L^{\,2}}$

$h_{vert} \leftarrow 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$ if $0 < Re \leq 30$

if $30 < Re \leq 1800$

$h_{vert} \leftarrow \frac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$

$Re_f \leftarrow \left[ 4.81 + \frac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} \right]^{0.82}$

if $Re > 1800$

$h_{vert} \leftarrow \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{-0.5} \cdot (Re^{0.75} - 253)} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}}$

$Re_f \leftarrow \left[ \frac{0.069 \cdot L \cdot k_L \cdot Pr_L^{0.5} \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left( \frac{g}{\nu_L^{\,2}} \right)^{\frac{1}{3}} - 151 \cdot Pr_L^{0.5} + 253 \right]^{\frac{4}{3}}$

$Q \leftarrow h_{vert} \cdot (L \cdot \pi \cdot D) \cdot (T_{sat} - T_s)$

$m_{condensed} \leftarrow \frac{Q}{h_{fg\_prime}}$

$AA \leftarrow \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ delta_L & h_{vert} & Re_f & Q & m_{condensed} \end{pmatrix}$

AA

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**Note:** Above program for vertical cylinder is similar to the one for vertical plate written earlier, except that now, heat transfer area is As = (π.D.L). Then heat transferred, Q and m_cond are calculated as earlier. Study the program shown above.

---

**Prob.3.2.5.** Consider a vertical tube, 1 m high, 80 mm dia, maintained at a uniform temp of 50 C, exposed to sat. steam at atm. pressure. Find out the heat transfer and steam condensation rate.

**Mathcad Solution:**

**Let us use the Mathcad Function for condensation on a vertical cylinder, written above:**

Data:

$T_s := 50 \ C \quad T_{sat} := 100 \ C \qquad L := 1 \ m \qquad D := 0.08 \ m$

$$\text{FilmCondensation\_Steam\_VertCyl}(T_s, T_{sat}, L, D) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 2.1742 \times 10^{-4} & 5.6045 \times 10^{3} & 1.1828 \times 10^{3} & 7.0428 \times 10^{4} & 0.0294 \end{pmatrix}$$

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**We see that:**

**Re_f = 1182.8 i.e. 30 < Re_f < 1800, so it is 'laminar-wavy' film region.**

**Heat transfer rate, Q = 70428 W … Ans.**

**Condensation rate, m_cond = 0.0294 kg/s … Ans.**

---

**Plot m_cond against Ts for 20 < Ts < 50 C:**

$T_s := 20, 25 .. 50$ C … define a range variable for Ts

Note that m_cond is element (1,4) in the output Matrix of the above Function.

***Remember that numbering of rows and columns starts from zero in Mathcad, by default.***

Then, we have:

$T_s =$ $\quad$ $\text{FilmCondensation\_Steam\_VertCyl}(T_s, T_{sat}, L, D)_{1,4}$

| | |
|---|---|
| 20 | 0.038 |
| 25 | 0.037 |
| 30 | 0.036 |
| 35 | 0.034 |
| 40 | 0.033 |
| 45 | 0.031 |
| 50 | 0.029 |

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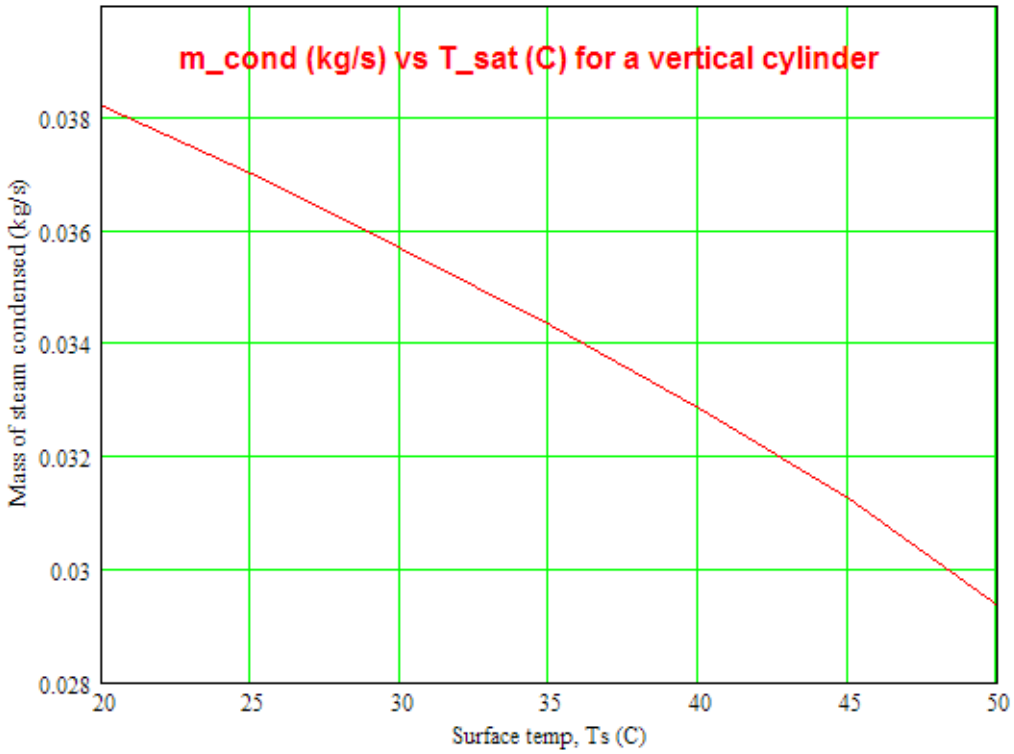
**And, plot the results:**

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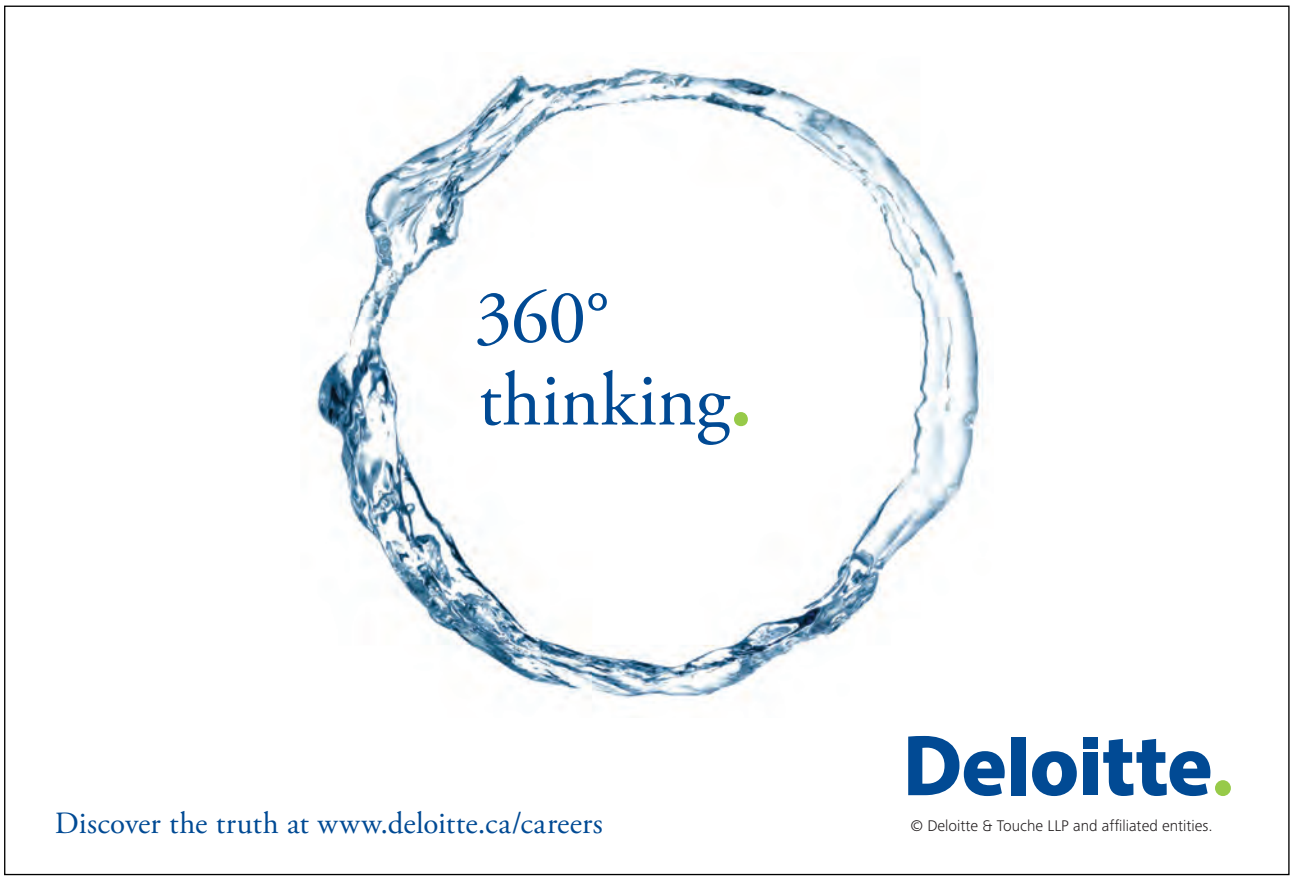


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**Prob.3.2.6.** Dry, sat. steam at a pressure of 2.45 bar condenses on the surface of a vertical tube of 40 mm dia and height 1 m. Tube surface temp is 117 C. Estimate the thickness of the condensate film and local heat transfer coeff. at a distance of 0.2 m from the upper end of the tube. [VTU – M.Tech. – Dec. 2010]

**Mathcad Solution:**

At 2.45 bar, sat. temp. of water is: Tsat = 126.75 deg.C. Ts is given as 117 C.

**Let us use the Mathcad Function for condensation on a vertical cylinder, written above:**

We get:

Data:

$T_s := 117\ C \quad T_{sat} := 126.75\ C \quad L := 0.2\ m \quad D := 0.04\ m$

$$\text{FilmCondensation\_Steam\_VertCyl}(T_s, T_{sat}, L, D) = \begin{pmatrix} \text{"delta\_L(m)"} & \text{"h\_avg(W/m\^2.C)"} & \text{"Re\_f"} & \text{"Q (W)"} & \text{"m\_cond (kg/s)"} \\ 8.929 \times 10^{-5} & 1.1612 \times 10^{4} & 175.9457 & 2.8456 \times 10^{3} & 1.2867 \times 10^{-3} \end{pmatrix}$$

Thus:

**Thickness of film at x = 0.2 m = delta_L = 0.0893 mm…..Ans.**

**Avg. heat transfer coeff = 11341 W/m^2.C**

Therefore, local heat transfer coeff is obtained from: h_avg = (4/3).h_x

**i.e. h_x = h_avg.(3/4) = 8506 W/m^2.C ….Ans.**

==========

**Prob.3.2.7.** A horizontal tube, 3 cm in dia has its surface temp maintained at 30 C. Steam at 7.38 kPa pressure condenses over it. Determine the rate of heat transfer and the rate of condensation per unit length of the tube.

**Mathcad Solution:**

Let us write a Mathcad Function for condensation of steam on horizontal pipe, using the equation given in the beginning of the Chapter:

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## Mathcad Function to find h_horizl, Q and m for Film condensation of steam on a horizontal cylinder:

**Input:** Ts, Tsat (C), D (m)

**Output:** h (W/m^2.C), Q (W), m_condensed (kg/s)

**Note:** Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) :=$$

return "Ts must be less than Tsat ! " if $T_s - T_{sat} \geq 0$

$T_f \leftarrow \dfrac{T_s + T_{sat}}{2}$

$\text{rho}_L \leftarrow \dfrac{1}{\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, T_f + 273.15)}$

$\text{rho}_V \leftarrow \dfrac{1}{\text{vg\_H2O}(\text{TempK}, \text{H2Ov\_g}, T_{sat} + 273.15)}$

$h_{fg} \leftarrow \text{h\_fg\_H2O}(\text{TempK}, \text{H2Oh\_fg}, T_{sat} + 273.15)$

$\text{mu}_L \leftarrow \text{mu\_f\_H2O}(\text{TempK}, \text{H2Omu\_f}, T_f + 273.15)$

$k_L \leftarrow \text{k\_f\_H2O}(\text{TempK}, \text{H2Ok\_f}, T_f + 273.15)$

$\text{cp}_L \leftarrow \text{cp\_f\_H2O}(\text{TempK}, \text{H2Ocp\_f}, T_f + 273.15)$

$h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot \text{cp}_L \cdot (T_{sat} - T_s)$

$g \leftarrow 9.81$

$$h_{horizl} \leftarrow 0.729 \left[ \frac{g \cdot \text{rho}_L \cdot (\text{rho}_L - \text{rho}_V) \cdot h_{fg\_prime} \cdot k_L^{\,3}}{\text{mu}_L \cdot (T_{sat} - T_s) \cdot D} \right]^{\frac{1}{4}}$$

$A_s \leftarrow \pi \cdot D \cdot L$

$Q \leftarrow h_{horizl} \cdot A_s \cdot (T_{sat} - T_s)$

$m_{cond} \leftarrow \dfrac{Q}{h_{fg\_prime}}$

$$\begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ h_{horizl} & Q & m_{cond} \end{pmatrix}$$

In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

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Line 9: Modified heat of evaporation, $h_{fg}$_prime is calculated here

Line 10: value of g is entered

Line 11: Average heat tr. coeff. h_horizl is calculated

Line 12: Surface area As is calculated

Line 13: Heat transferred, Q is calculated

Line 14: Mass of steam condensed, m_cond is calculatedas: m_cond = (Q/ hfg_prime)

Line 15: Output of the Function is a (2 × 5) Matrix. Its first row contains headings, and second row contains values of h_horizl (W/m^2.C), Q (W)and m_cond (kg/s) respectively.

---

Now, let us solve the above problem using this Function for horizl cylinder:

At 7.38 kPa, the sat. temp of water is: Tsat = 40 C, and Ts is given as 30 C.

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Following is the Mathcad worksheet:

**Data:**

$T_s := 30$ C $T_{sat} := 40$ C $L := 1$ m $D := 0.03$ m

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 9.308 \times 10^{3} & 8.773 \times 10^{3} & 3.603 \times 10^{-3} \end{pmatrix}$$

**Thus:**

**Heat transfer coeff. = h_horizl = 9308 W/m^2.C …. Ans.**

**Heat transferred, Q = 8773 W …. Ans.**

**Steam condensed = m_cond = 0.003603 kg/s … Ans.**

==========

**Prob.3.2.8.** A horizontal tube, 1 m long has its surface temp maintained at 70 C. Sat. steam at 1 atm pressure condenses over it. (a) What is the diameter required to achieve a condensation rate of 125 kg/h? (b) Plot the condensation rate as a function of surface temp for Ts between 70 and 90 C and for diameters of 125, 150 and 175 mm.(Ref. 3)

**Mathcad Solution:**

First, we shall assume a value for dia, D and then use the Mathcad Function for condensation od steam over horizl cylinders, written above. Then, we will use the 'Solve Block' of Mathcad to get the required dia to achieve 125 kg/h of condensation rate.

Following is the Mathcad worksheet:

**Data:**

$T_s := 70$ C $T_{sat} := 100$ C $L := 1$ m

$D := 0.03$ **m.....Assumed value**

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 8.8816 \times 10^{3} & 2.5112 \times 10^{4} & 0.0107 \end{pmatrix}$$

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We see that with assumed value of D = 0.03 m, we have m_cond = 0.0107 kg/s

But, we need m_cond = 125 kg/h.

Let us use 'Solve Block' of Mathcad:

Note that in the output Matrix, m_cond is element (1,2) of the Matrix.

***Remember that numbering of rows and columns starts from zero in Mathcad, by default.***

$m_{cond} := 125$ kg/h ... from data

Given

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L)_{1,2} = \frac{125}{3600}$$

D := Find(D)

D = 0.144 **m.... dia required to get 125 kg/h condensation.....Ans.**

---

**Plot m_cond as a function of Ts for various diameters:**

$T_s := 70, 72 .. 90$ C ... define Ts as a range variable

**For D = 0.125 m:**

| $T_s$ = | $\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, 0.125, L)_{1,2}$ |
|---|---|
| 70 | 0.031 |
| 72 | 0.03 |
| 74 | 0.028 |
| 76 | 0.027 |
| 78 | 0.025 |
| 80 | 0.024 |
| 82 | 0.022 |
| 84 | 0.02 |
| 86 | 0.018 |
| 88 | 0.016 |
| 90 | 0.014 |

---

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**For D = 0.150 m:**

| $T_s$ = | FilmCondensation_Steam_HorizlCyl_hQm$(T_s, T_{sat}, 0.15, L)_{1,2}$ |
|---|---|
| 70 | 0.036 |
| 72 | 0.034 |
| 74 | 0.033 |
| 76 | 0.031 |
| 78 | 0.029 |
| 80 | 0.027 |
| 82 | 0.025 |
| 84 | 0.023 |
| 86 | 0.021 |
| 88 | 0.019 |
| 90 | 0.017 |

**For D = 0.175 m:**

| $T_s$ = | FilmCondensation_Steam_HorizlCyl_hQm$(T_s, T_{sat}, 0.175, L)_{1,2}$ |
|---|---|
| 70 | 0.04 |
| 72 | 0.038 |
| 74 | 0.037 |
| 76 | 0.035 |
| 78 | 0.033 |
| 80 | 0.03 |
| 82 | 0.028 |
| 84 | 0.026 |
| 86 | 0.024 |
| 88 | 0.021 |
| 90 | 0.019 |

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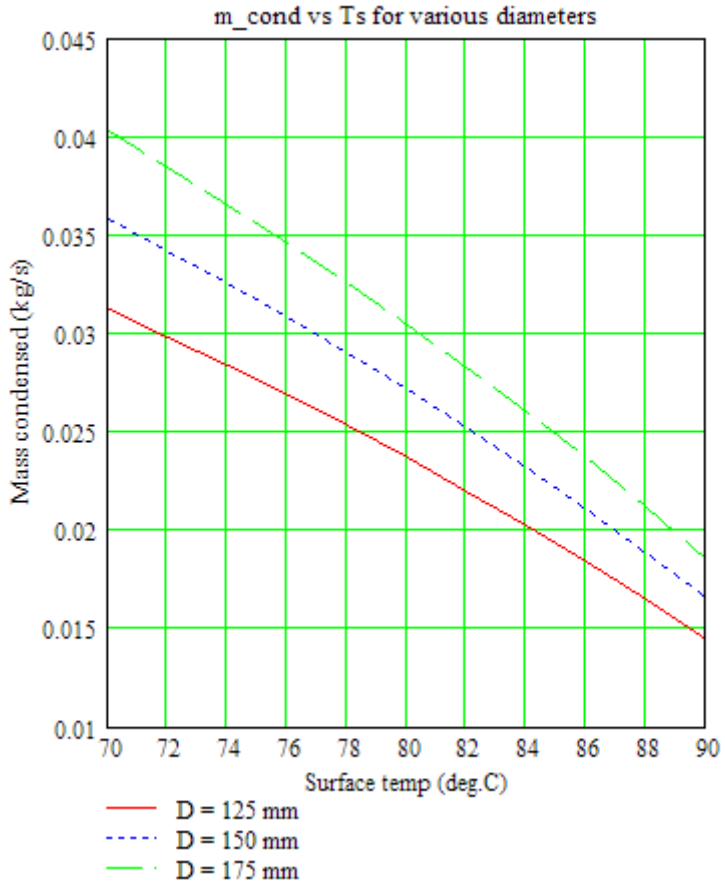
**Plot the results:**




==========

**Prob.3.2.9.** A horizontal tube, 1 m long has its surface temp maintained at 34 C. Sat. steam at 0.2 bar condenses over it. Determine the heat transfer rate and condensation rate.

**Mathcad Solution:**

At 0.2 bar, we have: $T_{sat}$ = 60 C.

Use the Mathcad Function for a horizl cylinder.

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Following is the Mathcad worksheet:

**Data:**

$T_s := 34 \quad C \qquad T_{sat} := 60 \quad C \qquad L := 1 \quad m \qquad D := 0.05 \quad m.$

$$\text{FilmCondensation\_Steam\_HorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{"h (W/m\^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 6.9336 \times 10^{3} & 2.8317 \times 10^{4} & 0.0116 \end{pmatrix}$$

**Thus:**

**Heat transfer rate, Q = 28.317 kW/m …. Ans.**

**Condensation rate, mcond = 0.0116 kg/s …. Ans.**

==========

Above problem was on condensation on a single, horizontal tube.

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But, of **more practical interest** is the condensation on a vertical tier of horizontal tubes.

We come across such a case in heat exchangers, particularly **in steam condensers.**

**Let us write a Mathcad Function for condensation on a vertical tier of horizontal tubes:**

---

Condensation on a Tube bank: N horizontal tubes in a vertical tier:

**Mathcad Function to find h_horizl, Q, and m for Film condensation of steam on a vertical tier of N horizontal cylinders:**

**Input:** Ts, Tsat (C), D (m), N

**Output:** h (W/m^2.C), het transferred per Tier, Q_Tier (W/Tier), m_cond (kg/s) per Tier

**Note:** Take liquid properties at Tf = (Tsat + Ts)/2, and h_fg and vap. properties at Tsat.

$$\text{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N) := \left| \begin{array}{l} \text{return "Ts must be less than Tsat ! "} \quad \text{if } T_s - T_{sat} \geq 0 \\ T_f \leftarrow \frac{T_s + T_{sat}}{2} \\ \text{rho}_L \leftarrow \frac{1}{\text{vf\_H2O}(\text{TempK}, \text{H2Ov\_f}, T_f + 273.15)} \\ \text{rho}_V \leftarrow \frac{1}{\text{vg\_H2O}(\text{TempK}, \text{H2Ov\_g}, T_{sat} + 273.15)} \\ h_{fg} \leftarrow \text{h\_fg\_H2O}(\text{TempK}, \text{H2Oh\_fg}, T_{sat} + 273.15) \\ \text{mu}_L \leftarrow \text{mu\_f\_H2O}(\text{TempK}, \text{H2Omu\_f}, T_f + 273.15) \\ k_L \leftarrow \text{k\_f\_H2O}(\text{TempK}, \text{H2Ok\_f}, T_f + 273.15) \\ \text{cp}_L \leftarrow \text{cp\_f\_H2O}(\text{TempK}, \text{H2Ocp\_f}, T_f + 273.15) \\ h_{fg\_prime} \leftarrow h_{fg} + 0.68 \cdot \text{cp}_L \cdot (T_{sat} - T_s) \\ g \leftarrow 9.81 \\ h_{horizl\_N} \leftarrow 0.729 \cdot \left[ \frac{g \cdot \text{rho}_L \cdot (\text{rho}_L - \text{rho}_V) \cdot h_{fg\_prime} \cdot k_L^{\,3}}{\text{mu}_L \cdot (T_{sat} - T_s) \cdot D \cdot N} \right]^{\frac{1}{4}} \\ A_s \leftarrow N \cdot \pi D \cdot L \\ Q_{Tier} \leftarrow h_{horizl\_N} \cdot A_s \cdot (T_{sat} - T_s) \\ m_{cond} \leftarrow \frac{Q_{Tier}}{h_{fg\_prime}} \\ \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ h_{horizl\_N} & Q_{Tier} & m_{cond} \end{pmatrix} \end{array} \right.$$

---

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In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

Line 9: Modified heat of evaporation, $h_{fg}$_prime is calculated here

Line 10: value of g is entered

Line 11: Average heat tr. coeff. for the tier, h_horizl_N is calculated; note that this eqn is similar to that for a single horizl tube, except that now, D is replaced by (N.D)

Line 12: Surface area As is calculated for the tier (i.e. for N tubes in the tier)

Line 13: Heat transferred for the tier, QTier is calculated

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Line 14: Mass of steam condensed for the N tubes of the tier, m_cond is calculatedas: m_cond =

(QTier/ hfg_prime)

Line 15: h, Q and m_cond are returned in a 2 × 3 Matrix. First row of the matrix gives column headings and the second row gives numerical values of h, Q and m_cond respectively.

---

**Prob.3.2.10.** Consider a heat exchanger with 20 tubes in a vertical column. Each tube has a dia of 1.5 cm, and is 1 m long. Sat. steam at 50 C condenses on the tubes, which are maintained at a surface temp of 20 C. Determine the average heat transfer coeff and rate of condensation of steam.

**Mathcad Solution:**

Use the Mathcad Function written above.

The worksheet is shown below:

**Data:**

$T_s := 20\ C \quad T_{sat} := 50\ C \quad L := 1\ m \quad D := 0.015\ m. \quad N := 20$

$$\text{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ 3.99054 \times 10^3 & 1.1283 \times 10^5 & 0.04572 \end{pmatrix}$$

**Thus:**

**Avg. heat transfer coeff. h = 3.99 kW/m^2.C … Ans.**

**Heat transfer, Q = 112.83 kW/Tier …. Ans.**

**Steam condensed, m_cond = 0.04572 kg/s = 164.592 kg/h …. Ans.**

==========

**Prob.3.2.11.** Condenser of a steam Power plant operates at 4.25 kPa. There are 100 horizontal tubes arranged in a 10 × 10 square array. Each tube is 8 m long, 3 cm in dia. Tube surface is at 20 C. Determine: (a) Rate of heat transfer (b) Rate of condensation of steam (Ref. 2)

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**Mathcad Solution:**

At 4.25 kPa pressure, we have: Tsat = 30 C.

Using the Mathcad Function for N horizontal tubes in a vertical Tier, we get:

**Data:**

$T_s := 20$ C $T_{sat} := 30$ C $L := 8$ m $D := 0.03$ m. $N := 10$

FilmCondensation_Steam_VertTierCyl_hQm$(T_s, T_{sat}, D, L, N)$ =

| "h (W/m^2.C" | "Q (W) per Tier" | "m_cond (kg/s) per Tier" |
|---|---|---|
| $4.89688 \times 10^3$ | $3.69216 \times 10^5$ | 0.15016 |

In the above worksheet, we got Q and m_cond per Tier.

But, there are 10 Tiers. So, multiplying the above values by 10, we get:

**Heat transferred, Q = 3692.16 kW …. Ans.**

**Steam condensed, m_cond = 1.5016 kg/s = 5406 kg/h …. Ans.**

---

**Now, if Tsat varies from 30 C to 54 C (corresponding to sat. pressure of 4.246 kPa to 15.02 kPa respectively), plot Q and mcond against Tsat:**

$T_{sat} := 30, 32 .. 54$ C…..define a range variable for Tsat

| $T_{sat}$ = | FilmCondensation_Steam_VertTierCyl_hQm$(T_s, T_{sat}, D, L, N)_{1,1} \cdot 10$ ….Q for 10 Tiers |
|---|---|
| 30 | $3.692 \cdot 10^6$ |
| 32 | $4.265 \cdot 10^6$ |
| 34 | $4.825 \cdot 10^6$ |
| 36 | $5.369 \cdot 10^6$ |
| 38 | $5.904 \cdot 10^6$ |
| 40 | $6.434 \cdot 10^6$ |
| 42 | $6.96 \cdot 10^6$ |
| 44 | $7.482 \cdot 10^6$ |
| 46 | $7.998 \cdot 10^6$ |
| 48 | $8.512 \cdot 10^6$ |
| 50 | $9.026 \cdot 10^6$ |
| 52 | $9.54 \cdot 10^6$ |
| 54 | $1.005 \cdot 10^7$ |

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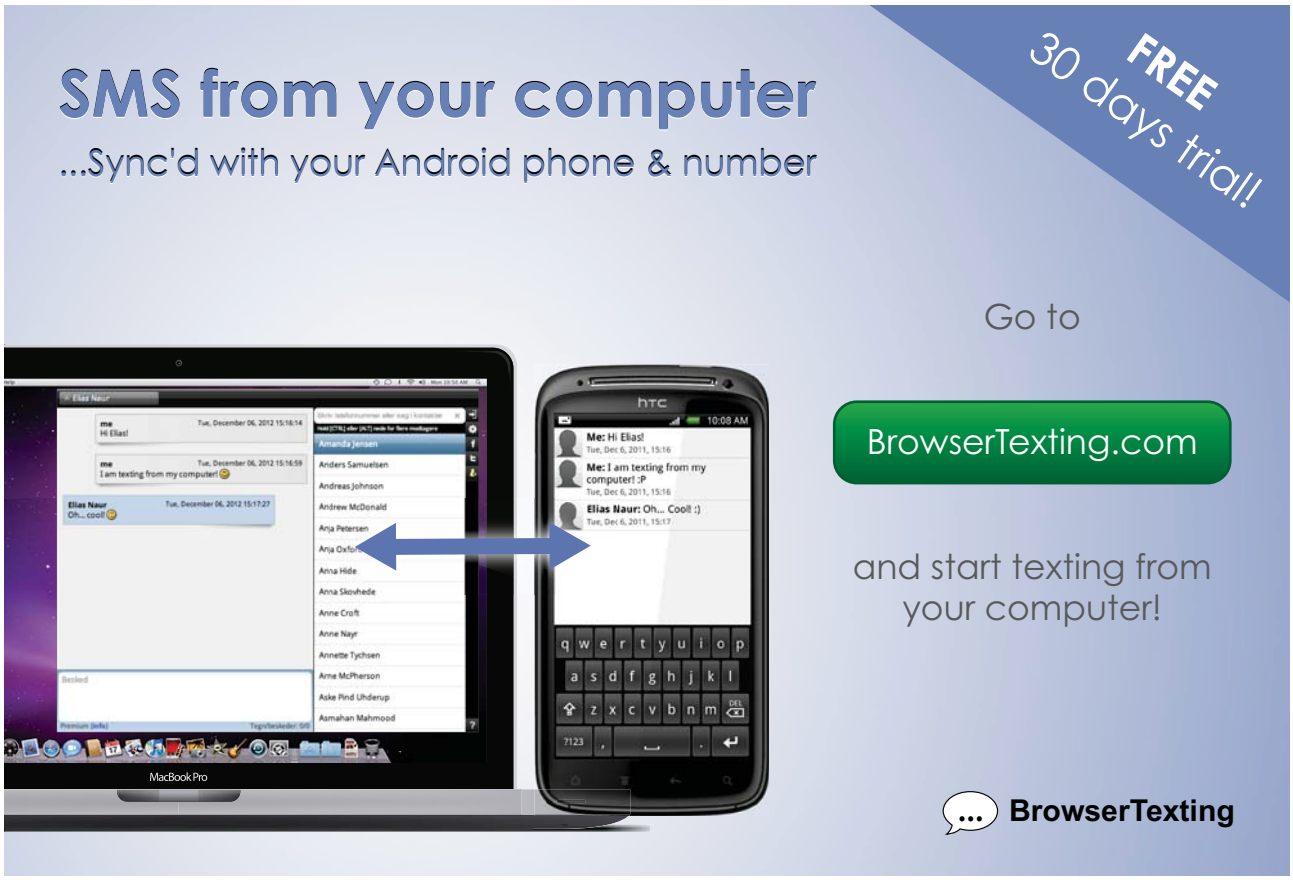
$T_{sat}$ = FilmCondensation_Steam_VertTierCyl_hQm$(T_s, T_{sat}, D, L, N)_{1,2}\cdot 10$ ..m_cond..for 10 Tiers

| | |
|---|---|
| 30 | 1.502 |
| 32 | 1.734 |
| 34 | 1.961 |
| 36 | 2.181 |
| 38 | 2.398 |
| 40 | 2.612 |
| 42 | 2.824 |
| 44 | 3.035 |
| 46 | 3.243 |
| 48 | 3.451 |
| 50 | 3.658 |
| 52 | 3.865 |
| 54 | 4.071 |

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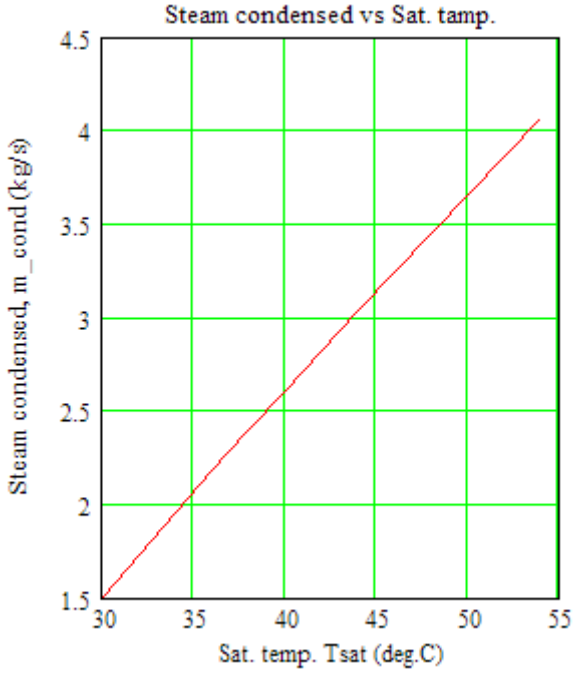
**And, Plot the results:**




==========

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**Prob.3.2.12.** A square array of 400 tubes, 15 mm OD is used to condense steam at atm. pressure. The tube walls are maintained at 88 C by a coolant flowing through the tubes. Calculate the amount of steam condensed per hour per unit length of tubes. [ VTU – M.Tech. – Dec. 2009–Jan. 2010]

**Mathcad Solution:**

There are totally 400 tubes, in a square array.

Therefore, we have: 20 tubes per Tier, and there are 20 Tiers.

Using the Mathcad Function already written, we get:

**Data:**

$T_s := 88\ C \quad T_{sat} := 100\ C \quad L := 1\ m \quad D := 0.015\ m. \quad N := 20$

$$\text{FilmCondensation\_Steam\_VertTierCyl\_hQm}(T_s, T_{sat}, D, L, N) = \begin{pmatrix} \text{"h (W/m^2.C"} & \text{"Q (W) per Tier"} & \text{"m\_cond (kg/s) per Tier"} \\ 6.42254 \times 10^3 & 7.26372 \times 10^4 & 0.0317 \end{pmatrix}$$

**Thus:**

**Steam condensed = m_cond = 0.0317 kg/s =**

0.0317·3600 = 114.12 **kg/h...Ans.**

==========

**Prob.3.2.13.** Sat. steam at 1.5 bar condenses inside a 75 mm dia horizontal pipe whose surface is maintained at 100 C. Assuming low vapour velocities and film condensation, estimate the heat transfer coeff. and the condensation rate per unit length of the pipe.

**Mathcad Solution:**

Let us first write a Mathcad Function for film condensation inside horizontal pipe using the equations given at the beginning of the Chapter.

---

**Film condensation inside horizl tubes: Chato's relation:**

**For low vapour velocities, i.e. Re_vap < 35000: Input:** Ts, Tsat (C), D (m), L (m)

**Input:** Ts, Tsat (C), D (m), L (m)

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**Output:** h_internal (W/m^2.C), Q (W) and m_cond (kg/s)

```
FilmCondensation_Steam_InsideHorizlCyl_hQm(Ts, Tsat, D, L) :=
  return "Ts must be less than Tsat ! "  if  Ts − Tsat ≥ 0
  Tf ← (Ts + Tsat)/2
  rhoL ← 1/vf_H2O(TempK, H2Ov_f, Tf + 273.15)
  rhoV ← 1/vg_H2O(TempK, H2Ov_g, Tsat + 273.15)
  hfg ← h_fg_H2O(TempK, H2Oh_fg, Tsat + 273.15)
  muL ← mu_f_H2O(TempK, H2Omu_f, Tf + 273.15)
  kL ← k_f_H2O(TempK, H2Ok_f, Tf + 273.15)
  cpL ← cp_f_H2O(TempK, H2Ocp_f, Tf + 273.15)
  g ← 9.81
  hfg_star ← hfg + (3/8)·cpL·(Tsat − Ts)
  hinternal ← 0.555·[g·rhoL·(rhoL − rhoV)·kL^3 / (muL·(Tsat − Ts)·D)·hfg_star]^(1/4)
  As ← π·D·L
  Q ← hinternal·As·(Tsat − Ts)
  mcond ← Q/hfg_star
  (" h (W/m^2.C"   "Q (W) "   "m_cond (kg/s)"
    hinternal          Q            mcond )
```

In the above program:

Line 1: defines the Function on LHS, and gives an error message if Ts > Tsat

Line 2: Tf = (Tsat + Ts)/2 is calculated

Line 3 to 8: Various properties of liquid and vapour are calculated using the property Functions for Sat. water already written.

Line 9: value of g is entered

Line 10: Modified heat of evaporation, $h_{fg}$_star is calculated here

Line 11: Average heat tr. coeff., h_internal is calculated

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Line 12: Surface area As is calculated for the tier (i.e. for N tubes in the tier)

Line 13: Heat transferred, Q is calculated

Line 14: Mass of steam condensed inside the tube, m_cond is calculatedas: m_cond =

(Q/ hfg_star)

Line 15: h, Q and m_cond are returned in a 2 × 3 Matrix. First row of the matrix gives column headings and the second row gives numerical values of h, Q and m_cond respectively.

---

Now, let us solve the above problem.

Note that corresponding to a pressure of 1.5 bar, for water: $T_{sat}$ = 111.35 C.

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Following is the Mathcad worksheet, wherein the above Mathcad Function is invoked:

**Data:**

$T_s := 100 \ C \qquad T_{sat} := 111.35 \ C \qquad D := 0.075 \ m \qquad L := 1 \ m$

$$\text{FilmCondensation\_Steam\_InsideHorizlCyl\_hQm}(T_s, T_{sat}, D, L) = \begin{pmatrix} \text{" h (W/m\^2.C"} & \text{"Q (W) "} & \text{"m\_cond (kg/s)"} \\ 7.21 \times 10^{3} & 1.928 \times 10^{4} & 8.591 \times 10^{-3} \end{pmatrix}$$

**Thus:**

**Heat transfer coeff, h = 7210 W/m^2.C ….. Ans.**

**Condensation rate = 0.008591 kg/s = 30.928 kg/h …. Ans.**

---

**(b) What is the length of tube required for a condensation rate of 50 kg/h?**

**Plot m_cond against L for m_cond varying from 10 to 70 kg/h:**

We will use the 'Solve Block' of Mathcad to easily calculate the value of L required to get m_cond = 50 kg/h:

$m_{cond} := 50 \quad kg/h$

Given

$$\text{FilmCondensation\_Steam\_InsideHorizlCyl\_hQm}(T_s, T_{sat}, D, L)_{1,2} = \frac{m_{cond}}{3600}$$

$L(m_{cond}) := \text{Find}(L)$

i.e. $L(m_{cond}) = 1.617$ **m....length of tube required to get a condensation rate of 50 kg/h .... Ans.**

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**Note: In the above, L is written as function of mcond. It is useful to draw the plot of L against mcond, as shown below:**

**To plot the results:**

Use the function L ($m_{cond}$) to get values of L for different values of $m_{cond}$:

$m_{cond} := 10, 15 .. 70$ kg/h.....define a range variable for m_cond

| $m_{cond}$ = | $L(m_{cond})$ = |
|---|---|
| 10 | 0.323 |
| 15 | 0.485 |
| 20 | 0.647 |
| 25 | 0.808 |
| 30 | 0.97 |
| 35 | 1.132 |
| 40 | 1.293 |
| 45 | 1.455 |
| 50 | 1.617 |
| 55 | 1.778 |
| 60 | 1.94 |
| 65 | 2.102 |
| 70 | 2.263 |

==========

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**EES Procedures for Condensation heat transfer:**

EES has the advantage that it has built-in Functions for properties of a large number of Fluids and materials.

So, it is very convenient to write Functions/Procedures for complicated equations, particularly if properties have to be calculated many times.

**We present below a few Procedures for condensation of steam on a few geometries:**

---

```
$UnitSystem SI Pa C J

PROCEDURE condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

"Condensation of any Fluid at T_sat on a vertical Plate (VP) held at T_s:"

"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."
```

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"Calculates h_avg for laminar, wavy and turbulent film condensation
based on value of Re_f"

"Note: positive x direction is from top of plate downwards; y dirn is from left to right"
"x is the distance from top, b is the breadth of plate perpendicular to paper"

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
delta_l:= ((4 * k_l * mu_l * (T_sat – T_s) * L)/(rho_l * (rho_l – rho_v) * g * h_fg_prime))^(1/4) "[m]….thickness of b. l. at a
distance L from top"

Re:= (4 * g * rho_l * (rho_l – rho_v) * delta_l^3)/(3 * mu_l^2) "…film Reynolds No."

If (Re> 0) and (Re<= 30) Then "laminar film"

h_avg:= 1.47 * k_l * Re^(-1/3) * (g/nu_l^2)^(1/3)

Else

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```
If (Re> 30) and (Re<= 1800) Then "wavy-laminar flow in film"

    h_avg:= ((Re* k_l)/(1.08 *Re^1.22 – 5.2)) * (g/nu_l^2)^(1/3)

    Re_f:= (4.81 + (3.7 * L * k_l * (T_sat – T_s) / (mu_l * h_fg_prime)) *(g / nu_l^2)^(1/3))^0.82

Else

If (Re > 1800) Then "turb. flow in film"

    h_avg:= ((Re * k_l)/(8750 + 58 * Pr_l^(-0.5) * (Re^0.75 – 253))) * (g/nu_l^2)^(1/3)

    Re_f:= (( 0.069* L * k_l * Pr_l^0.5 * (T_sat – T_s) / (mu_l * h_fg_prime)) * (g / nu_l^2)^(1/3) – 151
    * Pr_l^0.5 + 253)^(4/3)

EndIf
EndIf
EndIf

Q:= h_avg *(b * L) * (T_sat – T_s) "W"

m_condensed:= Q/h_fg_prime "kg/s"

END

" ---------- "

"Condensation on Vertical cylinder (VC):"

PROCEDURE condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a vertical cyl held at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22'
etc. etc."

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2
```

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"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s)"modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
delta_l:= ((4 * k_l * mu_l * (T_sat – T_s) * L)/(rho_l * (rho_l – rho_v) * g * h_fg_prime))^(1/4) "[m]….thickness of b. l. at a
distance L from top"

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```
Re:= (4 * g * rho_l * (rho_l – rho_v) * delta_l^3)/(3 * mu_l^2) "…film Reynolds No."

If (Re > 0) and (Re <= 30) Then "laminar film"

    h_avg:= 1.47 * k_l * Re^(-1/3) * (g/nu_l^2)^(1/3)

Else

 If (Re > 30) and (Re <= 1800) Then "wavy-laminar flow in film"

    h_avg:= ((Re * k_l)/(1.08 *Re^1.22 – 5.2)) * (g/nu_l^2)^(1/3)

    Re_f:= (4.81 + (3.7 * L * k_l * (T_sat – T_s) / (mu_l * h_fg_prime)) *(g / nu_l^2)^(1/3))^0.82

Else

 If (Re > 1800) Then "turb. flow in film"

    h_avg:= ((Re * k_l)/(8750 + 58 * Pr_l^(-0.5) * (Re^0.75 – 253))) * (g/nu_l^2)^(1/3)

    Re_f:= ((0.069* L * k_l * Pr_l^0.5 * (T_sat – T_s) / (mu_l * h_fg_prime)) * (g / nu_l^2)^(1/3) – 151
    * Pr_l^0.5 + 253)^(4/3)

EndIf
EndIf
EndIf

Q = h_avg * (pi * D *L)*(T_sat – T_s) "W"

mass_condensed = Q/h_fg_prime "kg/s"

END

"                                                                                                                                                    "
"----------------------------------------------------------------------------------------------------------------------------------------------------"

PROCEDURE condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a horizontal cyl at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22'
etc. etc."
```

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```
g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn
and liq film subcooling"
h_avg:= 0.729 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4)
"[W/m^2-C] …. avg heat tr coeff over L"
Q = h_avg * (pi * D *L)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"----------"

"Condensation on a Tube bank: N Horizontal Tubes in a vertical tier"

PROCEDURE condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_
condensed)

"Condensation of any Fluid at T_sat on a Bank of horizl tubes:"
"Condensation on a Tube bank: N horizontal tubes in a vertical tier"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ ='Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22'
etc. etc."
```

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"N horizontal tubes in a vertical tier:"
"N_toal is the total no. of tubes in the tube bank"

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
h_avg:= 0.729 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * N* D))^(1/4) "[W/m^2-C] …. avg heat tr coeff over L"
Q = h_avg * (N_total *pi * D *L)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"----------"

"Condensation on a Sphere:"

PROCEDURE condensation_Sphere_Fluid(Fluid$,T_sat, T_s, D: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat on a Sphere maintained at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."

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g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"

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```
h_fg_prime = h_fg + 0.68 * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"
h_avg:= 0.826 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4) "[W/m^2-C] …. avg heat tr coeff over the sphere"
Q = h_avg * (pi * D^2)*(T_sat – T_s) "W"
mass_condensed = Q/h_fg_prime "kg/s"
END

"=========================================================================="

$UnitSystem SI Pa C J

PROCEDURE condensation_InsideHCyl(Fluid$,T_sat, T_s, D, L, U_v: h_avg, Q, mass_condensed)

"Condensation of any Fluid at T_sat inside a Horizontal Cyl at T_s:"
"For Fluid$, use any of the many Fluids for which Data is available in EES.
In the calling program, add a line: Fluid$ = 'Steam_IAPWS', or 'Water', or 'Ammonia', or 'R12', or 'R22' etc. etc."

g:= 9.81[m/s^2]
T_f:= (T_sat + T_s)/2

"Properties of liquid at Tf:"

rho_l:=Density(Fluid$,T=T_f, x=0) "[kg/m^3]"
k_l:=Conductivity(Fluid$,T=T_f, x = 0) "[W/m-C]"
mu_l:=Viscosity(Fluid$,T=T_f,x=0) "[kg/m-s]"
nu_l = mu_l/rho_l "[m^2/s]"
cp_l=SpecHeat(Fluid$,T=T_f,x=0) "[J/kg-C]"
Pr_l=Prandtl(Fluid$,T=T_f,x=0)

"Properties of vapour and h_fg at Tsat:"

rho_v:=Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"
mu_v:=Viscosity(Fluid$,T=T_sat,x=1) "[kg/m-s]"

h_g:=Enthalpy(Fluid$,T=T_sat,x=1) "[J/kg]"
h_f:=Enthalpy(Fluid$,T=T_sat,x=0) "[J/kg]"
h_fg:= h_g – h_f "[J/kg]"
```

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h_fg_prime:= h_fg + (3/8) * cp_l * (T_sat – T_s) "modified h_fg….takes care of nonlinear temp distribn and liq film subcooling"

Re_vap:= rho_v * U_v * D/mu_v "..Vapour Reynolds No…must be < 35000!!"

If (Re_vap <= 35000) Then

h_avg:= 0.555 * ((g * rho_l *(rho_l – rho_v) * h_fg_prime * k_l^3)/(mu_l * (T_sat – T_s) * D))^(1/4) "[W/m^2-C] …. avg internal heat tr coeff over L"

Else

If (Re_vap > 35000) Then

CALL ERROR('Re_vap must be <= 35000. Now, Re_vap = XXXA6',Re_vap)

EndIf

EndIf

Q:= h_avg * (pi * D * L)*(T_sat – T_s) "W"

mass_condensed:= Q/h_fg_prime "kg/s"

END

"=========================================================================="

**Now, let us solve a few problems using these EES Procedures:**

**Prob. 3.2.14**. Sat. steam at atm pressure condenses on a 2 m high, 3 m wide vertical plate maintained at 80 C. Determine the avg heat transfer coeff., rate of heat transfer and the rate of condensation.

(b) If the plate is inclined to vertical at 30 deg. what will be these value s?

(c) For the case (a) draw the variation of condensation rate against Ts for 50 < Ts < 90 C.

**EES Solution:**

T_sat = 100 C since pressure is 1 atm.

Use the EES Procedure written above.

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We have:

**"Data:"**

T_sat = 100 [C]
T_s = 80 [C]
b = 3 [m]
L = 2 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

**Results:**

Main | condensation_VP_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| b = 3 [m] | $\delta_l$ = 0.0002002 [m] | Fluid$ = 'Steam_IAPWS' |
| $h_{avg}$ = 6207 [W/m$^2$-C] | L = 2 [m] | $m_{condensed}$ = 0.3219 [kg/s] |
| Q = 744860 [W] | $Re_f$ = 1291 | $T_s$ = 80 [C] |
| $T_{sat}$ = 100 [C] | | |

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Main | condensation_VP_Fluid

**Local variables in Procedure condensation_VP_Fluid (1 call, 0.02 sec)**

| | | |
|---|---|---|
| b=3 [m] | $cp_l$ =4205 [J/kg-C] | $\delta_l$ =0.0002002 [m] |
| Fluid$='Steam_IAPWS' | g=9.81 [$m/s^2$] | $h_{avg}$ =6207 [$W/m^2$-C] |
| $h_f$ =419169 [J/kg] | $h_{fg}$ =2.256E+06 [J/kg] | $h_{fg'}$ =2.314E+06 [J/kg] |
| $h_g$=2.676E+06 [J/kg] | $k_l$ =0.6752 [W/m-C] | L=2 [m] |
| $\mu_l$ =0.0003144 [kg/m-s] | $m_{condensed}$=0.3219 [kg/s] | $\nu_l$ =3.257E-07 [$m^2/s$] |
| $Pr_f$=1.958 | Q =744860 [W] | Re =989.1 |
| $Re_f$=1291 | $\rho_l$ =965.3 [$kg/m^3$] | $\rho_v$=0.5981 [$kg/m^3$] |
| $T_f$=90 [C] | $T_s$=80 [C] | $T_{sat}$ =100 [C] |

**Thus:**

**h_avg = 6207 W/m^2-C….ans.**

**Q = 744860 W…ns.**

**m_cond = 0.3219 kg/s…..Ans.**

---

**(b) If the plate is tilted at 30 deg. to vertical, heat tr. coeff. for that case is:**

h_inclined = h_vert * (cos(30))^(1/4).

Modify the program above as shown below:

**"Data:"**

T_sat = 100 [C]
T_s = 80 [C]
b = 3 [m]
L = 2 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

"For part (b)…plate inclined at 30 deg to vertical:"

h_fg_prime2 = 2.314E06 [J/kg] "…This is the same as h_fg_prime in part (a), copied from there"

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theta = 30 [deg]
h_inclined = h_avg * (cos (theta))^(1/4)
Q_inclined = h_inclined * (L * b) * (T_sat – T_s)
m_cond_inclined = Q_inclined /h_fg_prime2

So, we get:

Main | condensation_VP_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $b = 3$ [m] | $\delta_l = 0.0002002$ [m] | Fluid$ = 'Steam_IAPWS' |
| $h_{avg} = 6207$ [W/m$^2$-C] | $h_{fg,prime2} = 2.314E+06$ [J/kg] | $h_{inclined} = 5988$ [W/m$^2$-C] |
| $L = 2$ [m] | $m_{condensed} = 0.3219$ [kg/s] | $m_{cond,inclined} = 0.3105$ [kg/s] |
| $Q = 744860$ [W] | $Q_{inclined} = 718551$ [W] | $Re_f = 1291$ |
| $\theta = 30$ [deg] | $T_s = 80$ [C] | $T_{sat} = 100$ [C] |

Main | condensation_VP_Fluid

**Local variables in Procedure condensation_VP_Fluid (1 call, 0.02 sec)**

| | | |
|---|---|---|
| b=3 [m] | $cp_l$ =4205 [J/kg-C] | $\delta_l$ =0.0002002 [m] |
| Fluid$='Steam_IAPWS' | g=9.81 [m/s$^2$] | $h_{avg}$ =6207 [W/m$^2$-C] |
| $h_f$ =419169 [J/kg] | $h_{fg}$ =2.256E+06 [J/kg] | $h_{fg'}$ =2.314E+06 [J/kg] |
| $h_g$=2.676E+06 [J/kg] | $k_l$ =0.6752 [W/m-C] | L=2 [m] |
| $\mu_l$ =0.0003144 [kg/m-s] | $m_{condensed}$=0.3219 [kg/s] | $\nu_l$ =3.257E-07 [m$^2$/s] |
| $Pr_f$=1.958 | Q =744860 [W] | Re =989.1 |
| $Re_f$=1291 | $\rho_l$ =965.3 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $T_f$ =90 [C] | $T_s$=80 [C] | $T_{sat}$ =100 [C] |

**So,**

**h_inclined = 5988 W/m^2-C….ans.**
**Q_inclined = 718551 W…ns.**
**m_cond = 0.3105 kg/s…..Ans.**

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**P lot m_cond vs Ts for case (a), with 50 < Ts < 90 C:**

First, construct the Parametric Table:

Parametric Table

Table 1

| 1..9 | $T_s$ [C] | $h_{avg}$ [W/m2-C] | Q [W] | $m_{condensed}$ [kg/s] |
|---|---|---|---|---|
| Run 1 | 50 | 4968 | 1.490E+06 | 0.6213 |
| Run 2 | 55 | 5121 | 1.383E+06 | 0.5798 |
| Run 3 | 60 | 5287 | 1.269E+06 | 0.5353 |
| Run 4 | 65 | 5471 | 1.149E+06 | 0.4876 |
| Run 5 | 70 | 5678 | 1.022E+06 | 0.4363 |
| Run 6 | 75 | 5918 | 887635 | 0.3813 |
| Run 7 | 80 | 6207 | 744860 | 0.3219 |
| Run 8 | 85 | 6579 | 592094 | 0.2575 |
| Run 9 | 90 | 7109 | 426522 | 0.1867 |

Note that in the same Table, we have obtained the values of h_avg and Q also for various values of Ts.

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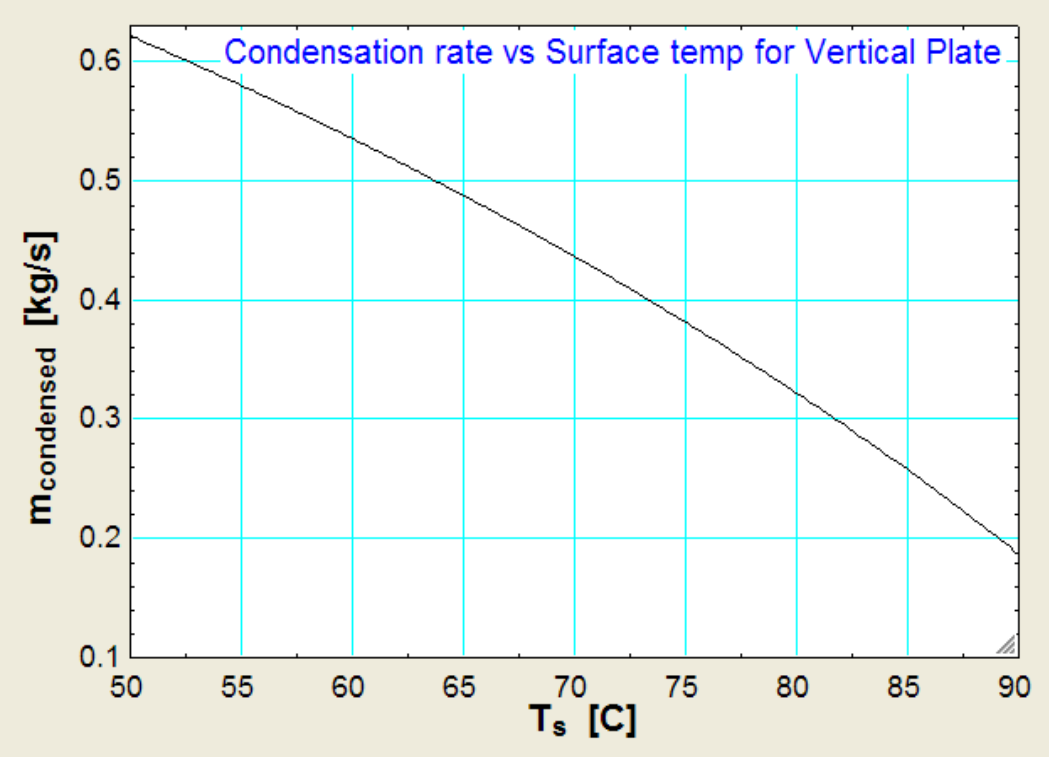
**Now, plot the results:**




==========

**Prob. 3.2.15**. Refrigerant-12 (R12) condenses on a vertical plate (size: 1 m × 1 m) at 40 C. Plate is held at 20 C. Determine the value of heat transfer coeff and the condensation rate.

**EES Solution:**

Use the EES procedure for vertical plate as in the previous problem.

For Fluid$ take Fluid$ = 'R12'

Following is the program:

**"Data:"**

T_sat = 40 [C]
T_s = 20 [C]
b = 1 [m]
L = 1 [m]

Fluid$ = 'R12'

CALL condensation_VP_Fluid(Fluid$,T_sat, T_s, b, L: delta_l, h_avg, Re_f, Q, m_condensed)

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Press F2 and we get:

Main | condensation_VP_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| b = 1 [m] | $\delta_l$ = 0.0001503 [m] | Fluid$ = 'R12' |
| $h_{avg}$ = 882.4 [W/m$^2$-C] | L = 1 [m] | $m_{condensed}$ = 0.1245 [kg/s] |
| Q = 17648 [W] | $Re_f$ = 2205 | $T_s$ = 20 [C] |
| $T_{sat}$ = 40 [C] | | |

Main | condensation_VP_Fluid

**Local variables in Procedure condensation_VP_Fluid (1 call, 0.05 sec)**

| | | |
|---|---|---|
| b=1 [m] | $cp_l$ =969.4 [J/kg-C] | $\delta_l$ =0.0001503 [m] |
| Fluid$='R12' | g=9.81 [m/s$^2$] | $h_{avg}$ =882.4 [W/m$^2$-C] |
| $h_f$ =74571 [J/kg] | $h_{fg}$ =128625 [J/kg] | $h_{fg'}$ =141809 [J/kg] |
| $h_g$=203196 [J/kg] | $k_l$ =0.06732 [W/m-C] | L=1 [m] |
| $\mu_l$ =0.0002109 [kg/m-s] | $m_{condensed}$=0.1245 [kg/s] | $\nu_l$ =1.632E-07 [m$^2$/s] |
| $Pr_f$=3.037 | Q =17648 [W] | Re =1597 |
| $Re_f$=2205 | $\rho_l$ =1292 [kg/m$^3$] | $\rho_v$=55.01 [kg/m$^3$] |
| $T_f$=30 [C] | $T_s$=20 [C] | $T_{sat}$ =40 [C] |

**Thus:**

**h_avg = 882.4 W/m^2-C….Ans.**
**Q = 17648 W…Ans.**
**m_cond = 0.1245 kg/s…..Ans.**

==========

**Prob. 3.2.16**. Sat. steam at 55 C is to be condensed at a rate of 10 kg/h on the outside of a 3 cm OD vertical tube whose surface is maintained at 45 C. Determine the tube length required.

**EES Solution:**

Use the EES Procedure written above.

We have:

**"Data:"**

T_sat = 55 [C]
T_s = 45 [C]

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D = 0.03 [m]

Fluid$ = 'Steam_IAPWS'

mass_condensed = 10 * convert(kg/h, kg/s)

CALL condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)

**Note:** In the above CALL to the Procedure, input L is not known; however, output: mass_condensed is known. It is converted to kg/s from kg/h, since all units are required to be in SI and mass rate is kg/s.

Observe the ease with which EES does these calculations of trial and error.

We get, on clicking F2 to solve:

Main | condensation_VC_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| D = 0.03 [m] | $\delta_l$ = 0.0001637 [m] | Fluid$ = 'Steam_IAPWS' |
| $h_{avg}$ = 6033 [W/m$^2$C] | L = 1.172 [m] | $mass_{condensed}$ = 0.002778 [kg/s] |
| Q = 6662 [W] | $T_s$ = 45 [C] | $T_{sat}$ = 55 [C] |

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Main | condensation_VC_Fluid

**Local variables in Procedure condensation_VC_Fluid (5 calls, 0.02 sec)**

| | | |
|---|---|---|
| $cp_l$ =4182 [J/kg-C] | D =0.03 [m] | $\delta_l$ =0.0001637 [m] |
| Fluid$='Steam_IAPWS' | g=9.81 [$m/s^2$] | $h_{avg}$ =6033 [$W/m^2$-C] |
| $h_f$ =230259 [J/kg] | $h_{fg}$ =2.370E+06 [J/kg] | $h_{fg'}$ =2.398E+06 [J/kg] |
| $h_g$=2.600E+06 [J/kg] | $k_l$ =0.6435 [W/m-C] | L=1.172 [m] |
| $mass_{condensed}$ =0.002778 [kg/s] | $\mu_l$ =0.0005468 [kg/m-s] | $\nu_l$ =5.535E-07 [$m^2/s$] |
| $Pr_f$=3.553 | Q =6662 [W] | Re =187.3 |
| $Re_f$=210.3 | $\rho_l$ =988 [$kg/m^3$] | $\rho_v$=0.1046 [$kg/m^3$] |
| $T_f$=50 [C] | $T_s$=45 [C] | $T_{sat}$ =55 [C] |

**Thus: Length of tube required = L = 1.172 m ….. Ans.**

**Note** that h, Q, mass_cond, and all properties are also immediately available. This becomes very convenient for verification, in case we get any unreasonable results.

---

**(b) Keeping the tube length as 1.172 m just obtained, plot mass condensed against Ts for tube diameters of 2 cm, 3 cm and 4 cm:**

Let Ts vary from 25 C to 50 C:

We modify the program as follows:

**"Data:"**

T_sat = 55 [C]
{T_s = 45 [C]}
D = 0.03 [m]
L = 1.172[m]

{mass_condensed = 10 * convert(kg/h, kg/s)}

Fluid$ = 'Steam_IAPWS'

CALL condensation_VC_Fluid(Fluid$,T_sat, T_s, D, L: delta_l, h_avg, Q, mass_condensed)

---

Note that in the above program, Ts is 'commented out' since it is the variable in the Parametric Table.

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L is entered as 1.21 m. Then, we call the Procedure to get mass_condensed.

Following are the 3 parametric Tables for D = 2, 3 and 4 cm:

**D = 2cm:**

Parametric Table

Table 1- D = 2 cm | Table 2 - D = 3 cm | Table

| 1..6 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 25 | 0.004162 |
| Run 2 | 30 | 0.003674 |
| Run 3 | 35 | 0.003132 |
| Run 4 | 40 | 0.00253 |
| Run 5 | 45 | 0.001852 |
| Run 6 | 50 | 0.001071 |

**D = 3cm:**

Parametric Table

Table 1- D = 2 cm | Table 2 - D = 3 cm | Table

| 1..6 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 25 | 0.006243 |
| Run 2 | 30 | 0.00551 |
| Run 3 | 35 | 0.004698 |
| Run 4 | 40 | 0.003794 |
| Run 5 | 45 | 0.002779 |
| Run 6 | 50 | 0.001606 |

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**D = 4 cm:**

Parametric Table

Table 2 - D = 3 cm | Table 3 - D = 4 cm

| 1..6 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 25 | 0.008325 |
| Run 2 | 30 | 0.007347 |
| Run 3 | 35 | 0.006264 |
| Run 4 | 40 | 0.005059 |
| Run 5 | 45 | 0.003705 |
| Run 6 | 50 | 0.002141 |

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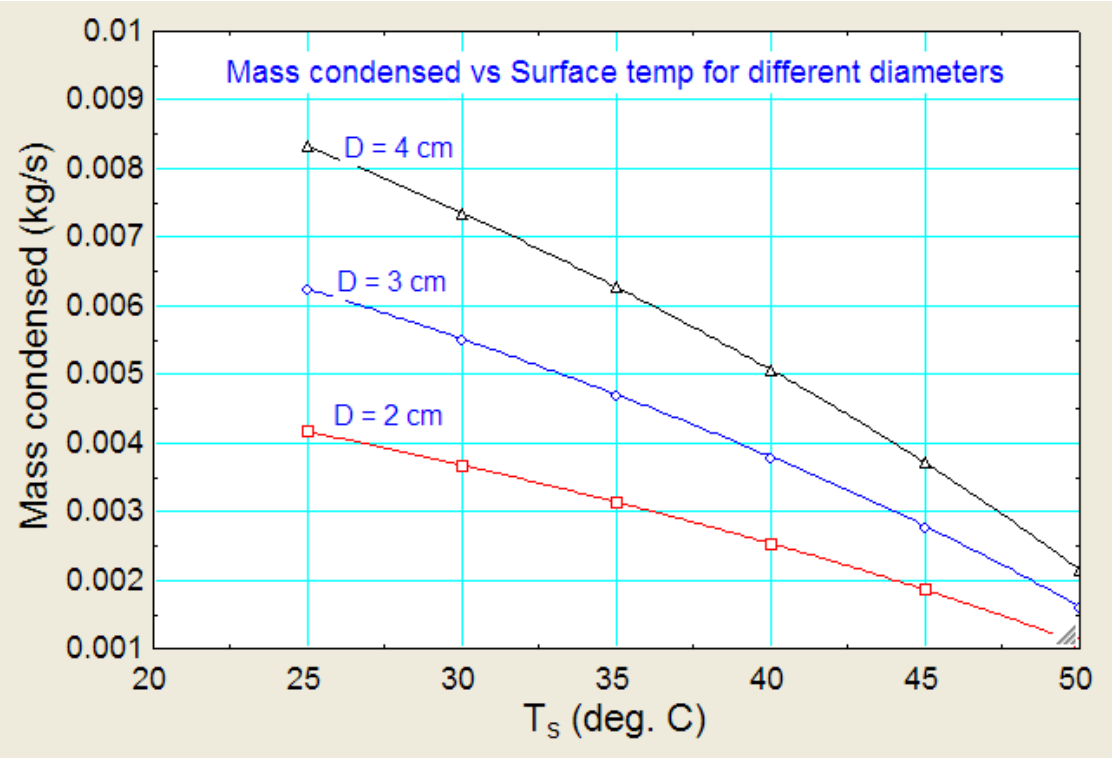
**Now, plot them on the same plot:**




==========

**Prob.3.2.17.** A horizontal tube, 1 m long has its surface temp maintained at 70 C. Sat. steam at 1 atm pressure condenses over it. (a) What is the diameter required to achieve a condensation rate of 125 kg/h? (b) Plot the condensation rate as a function of surface temp for Ts between 70 and 90 C and for diameters of 125, 150 and 175 mm. (Ref. 3)

**EES Solution:**

**This is the same as Prob. 3.2.8, which was solved with Mathcad.**

Now, we shall solve it with EES, using the Procedure for a horizontal cylinder written above.

Following is the EES program with a call to the Procedure:

**"Data:"**

T_sat = 100 [C]
T_s = 70 [C]
L = 1[m]

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Fluid$ = 'Steam_IAPWS'

mass_condensed = 125 * convert(kg/h, kg/s)

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

Note that, in the above program, one of the inputs, viz. D is not known; however, one of the outputs i.e. mass_condensed is given. It is converted here from kg/h to kg/s since SI units are to be used throughout.

***It is interesting to see the ease with which this is solved with EES:***

Click F2 to solve:

We get:

Main | condensation_HC_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $D = 0.1441$ [m] | Fluid$ = 'Steam_IAPWS' | $h_{avg} = 5988$ [W/m$^2$-C] |
| $L = 1$ [m] | $mass_{condensed} = 0.03472$ [kg/s] | $Q = 81324$ [W] |
| $T_s = 70$ [C] | $T_{sat} = 100$ [C] | |

Main | condensation_HC_Fluid

**Local variables in Procedure condensation_HC_Fluid (12 calls, 0.03 sec)**

| | | |
|---|---|---|
| $cp_l$ =4201 [J/kg-C] | D =0.1441 [m] | Fluid$='Steam_IAPWS' |
| g=9.81 [m/s$^2$] | $h_{avg}$ =5988 [W/m$^2$-C] | $h_f$ =419169 [J/kg] |
| $h_{fg}$ =2.256E+06 [J/kg] | $h_{fg'}$ =2.342E+06 [J/kg] | $h_g$=2.676E+06 [J/kg] |
| $k_l$ =0.6728 [W/m-C] | L=1 [m] | $mass_{condensed}$ =0.03472 [kg/s] |
| $\mu_l$ =0.0003333 [kg/m-s] | $\nu_l$ =3.441E-07 [m$^2$/s] | Pr=2.081 |
| Q =81324 [W] | $\rho_l$ =968.6 [kg/m$^3$] | $\rho_v$=0.5981 [kg/m$^3$] |
| $T_f$=85 [C] | $T_s$=70 [C] | $T_{sat}$ =100 |

**Thus:**
**Dia of tube to get a condensation rate of 125 kg/h (i.e. 0.03472 kg/s) is = D = 0.1441 m …Ans.**

**Note: This matches with the result we got with Mathcad earlier.**

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**To plot mass_cond vs Ts for = 125, 150 and 175 mm:**

Compute the Parametric Tables for these three diameters:

Modify the earlier program as follows:

**"Data:"**

T_sat = 100 [C]
{T_s = 70 [C]}
L = 1[m]
D = 0.125 [m]

Fluid$ = 'Steam_IAPWS'

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

In the above, D is entered as 0.125 m. Ts is 'commented out' since it is now the variable for the Parametric Table.

We have 3 Parametric Tables for three values of Diameters:

**D = 125 mm:**

Parametric Table

Table 1- D = 125 mm | Table 2 - D = 150 mm

| 1..11 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 70 | 0.03121 |
| Run 2 | 72 | 0.02979 |
| Run 3 | 74 | 0.02832 |
| Run 4 | 76 | 0.0268 |
| Run 5 | 78 | 0.02523 |
| Run 6 | 80 | 0.02361 |
| Run 7 | 82 | 0.02192 |
| Run 8 | 84 | 0.02016 |
| Run 9 | 86 | 0.01833 |
| Run 10 | 88 | 0.0164 |
| Run 11 | 90 | 0.01438 |

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**D = 150 mm:**

Parametric Table

Table 1 - D = 125 mm | Table 2 - D = 150 mm

| 1..11 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 70 | 0.03578 |
| Run 2 | 72 | 0.03415 |
| Run 3 | 74 | 0.03247 |
| Run 4 | 76 | 0.03073 |
| Run 5 | 78 | 0.02893 |
| Run 6 | 80 | 0.02706 |
| Run 7 | 82 | 0.02513 |
| Run 8 | 84 | 0.02312 |
| Run 9 | 86 | 0.02101 |
| Run 10 | 88 | 0.01881 |
| Run 11 | 90 | 0.01648 |

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**D = 175 mm:**

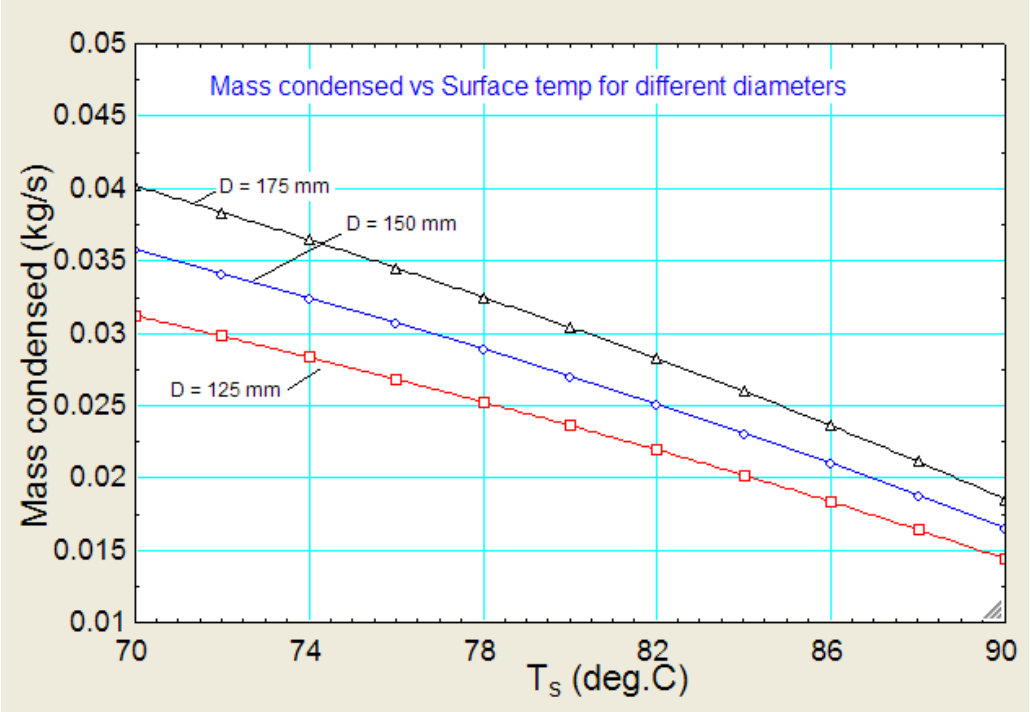
Parametric Table

Table 2 - D = 150 mm | Table 3- D = 175 mm

| 1..11 | 1 $T_s$ [C] | 2 $mass_{condensed}$ [kg/s] |
|---|---|---|
| Run 1 | 70 | 0.04017 |
| Run 2 | 72 | 0.03834 |
| Run 3 | 74 | 0.03645 |
| Run 4 | 76 | 0.03449 |
| Run 5 | 78 | 0.03247 |
| Run 6 | 80 | 0.03038 |
| Run 7 | 82 | 0.02821 |
| Run 8 | 84 | 0.02595 |
| Run 9 | 86 | 0.02359 |
| Run 10 | 88 | 0.02111 |
| Run 11 | 90 | 0.0185 |

---

**Now, plot the results:**




**Note: These results match with those obtained with Mathcad in Prob. 3.2.8.**

==========

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**Prob. 3.2.18.** Sat. NH3 vapour at 10 C condenses on the outside of a 2 cm dia, 5 m long horizontal tube whose surface is maintained at -10 C. Determine: (a) rate of heat transfer (b) rate of condensation. (Ref. 2)

**EES Solution:**

**Use the EES procedure written for condensation of a Fluid on the outside of a horizl cylinder:**

**"Data:"**

T_sat = 10 [C]
T_s = -10 [C]
L =5 [m]
D = 0.02 [m]

Fluid$ = 'Ammonia'

CALL condensation_HC_Fluid(Fluid$,T_sat, T_s, D, L: h_avg, Q, mass_condensed)

**Press F2 to solve, and we get:**

Main | condensation_HC_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $D = 0.02$ [m] | Fluid$ = 'Ammonia' | $h_{avg} = 7807$ [W/m$^2$-C] |
| $L = 5$ [m] | $mass_{condensed} = 0.03808$ [kg/s] | $Q = 49050$ [W] |
| $T_s = -10$ [C] | $T_{sat} = 10$ [C] | |

Main | condensation_HC_Fluid

**Local variables in Procedure condensation_HC_Fluid (1 call, 0.03 sec)**

| | | |
|---|---|---|
| $cp_l = 4615$ [J/kg-C] | $D = 0.02$ [m] | Fluid$='Ammonia' |
| $g = 9.81$ [m/s$^2$] | $h_{avg} = 7807$ [W/m$^2$-C] | $h_f = 246379$ [J/kg] |
| $h_{fg} = 1.225E+06$ [J/kg] | $h_{fg'} = 1.288E+06$ [J/kg] | $h_g = 1.472E+06$ [J/kg] |
| $k_l = 0.5594$ [W/m-C] | $L = 5$ [m] | $mass_{condensed} = 0.03808$ [kg/s] |
| $\mu_l = 0.0001702$ [kg/m-s] | $\nu_l = 2.666E-07$ [m$^2$/s] | $Pr_f = 1.405$ |
| $Q = 49050$ [W] | $\rho_l = 638.7$ [kg/m$^3$] | $\rho_v = 4.885$ [kg/m$^3$] |
| $T_f = 0$ [C] | $T_s = -10$ [C] | $T_{sat} = 10$ |

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**Thus:**

**h_avg = 7807 W/m^2-C….Ans.**

**Q = 49050 W…Ans.**

**m_cond = 0.03808 kg/s**

==========

**Prob. 3.2.19.** A steam condenser consists of a square array of 400 horizontal tubes, each 6 mm in diameter. The tubes are exposed to exhaust steam arriving from the turbine at a pressure of 0.1 bar. If the tube surface temperature is maintained at a temperature of 25 C by circulating cold water through the tubes, determine the heat transfer coefficient and the rate at which the steam is condensed per unit length of tubes for the entire array. Assume laminar film condensation and that there are no condensable gases mixed with steam. (Ref. 1)

**EES Solution:**

Now, we shall solve this problem using the Procedure for an array of horizontal cylinders in a vertical tier, written above.

Following is the EES program with a call to the Procedure:

**"Data:"**

T_sat = 45.8 [C]"..Tsat for Water at a pressure of 0.1 bar"
T_s = 25 [C]
L = 1[m]
D = 0.006 [m]
N_total = 400
N = 20 " i.e. N = 400^0.5, since there are 400 tubes in a square array."
Fluid$ = 'Steam_IAPWS'

CALL condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_condensed)

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**Click F2 to solve, and we get:**

Main | condensation_HTBank_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| D = 0.006 [m] | Fluid$ = 'Steam_IAPWS' | $h_{avg}$ = 5499 [W/m$^2$-C] |
| L = 1 [m] | $mass_{condensed}$ = 0.3518 [kg/s] | N = 20 |
| $N_{total}$ = 400 | Q = 862415 [W] | $T_s$ = 25 [C] |
| $T_{sat}$ = 45.8 [C] | | |

Main | condensation_HTBank_Fluid

**Local variables in Procedure condensation_HTBank_Fluid (1 call, 0.02 sec)**

| | | |
|---|---|---|
| $cp_l$ =4180 [J/kg-C] | D =0.006 [m] | Fluid$='Steam_IAPWS' |
| g=9.81 [m/s$^2$] | $h_{avg}$ =5499 [W/m$^2$-C] | $h_f$ =191782 [J/kg] |
| $h_{fg}$ =2.392E+06 [J/kg] | $h_{fg'}$ =2.451E+06 [J/kg] | $h_g$=2.584E+06 [J/kg] |
| $k_l$ =0.6239 [W/m-C] | L=1 [m] | $mass_{condensed}$ =0.3518 [kg/s] |
| $\mu_l$ =0.0007136 [kg/m-s] | N =20 | $\nu_l$ =7.180E-07 [m$^2$/s] |
| $N_{total}$ =400 | $Pr_F$4.781 | Q =862415 [W] |
| $\rho_l$ =993.8 [kg/m$^3$] | $\rho_v$=0.06815 [kg/m$^3$] | $T_f$=35.4 [C] |
| $T_s$=25 [C] | $T_{sat}$ =45.8 [C] | |

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**Thus:**

**Heat transfer coeff., h_avg = 5499 W/m^2-C….Ans.**

**Total heat transfer for the array, Q = 862415 W ….Ans.**

**Mass condensed for the entire array = 0.3518 kg/s = 1266 kg/h … Ans.**

---

**Now, if Tsat varies from 30 C to 54 C (corresponding to sat. pressure of 4.246 kPa to 15.02 kPa respectively), plot Q and mcond against Tsat:**

First, compute the Parametric Table:

Table 1

| 1..13 | 1 $T_{sat}$ [C] | 2 Q [W] | 3 $mass_{condensed}$ [kg/s] |
|---|---|---|---|
| Run 1 | 30 | 279962 | 0.1145 |
| Run 2 | 32 | 363016 | 0.1485 |
| Run 3 | 34 | 441539 | 0.1805 |
| Run 4 | 36 | 516976 | 0.2113 |
| Run 5 | 38 | 590170 | 0.2411 |
| Run 6 | 40 | 661665 | 0.2702 |
| Run 7 | 42 | 731833 | 0.2988 |
| Run 8 | 44 | 800946 | 0.3269 |
| Run 9 | 46 | 869207 | 0.3546 |
| Run 10 | 48 | 936771 | 0.382 |
| Run 11 | 50 | 1.004E+06 | 0.4092 |
| Run 12 | 52 | 1.070E+06 | 0.4362 |
| Run 13 | 54 | 1.136E+06 | 0.4629 |

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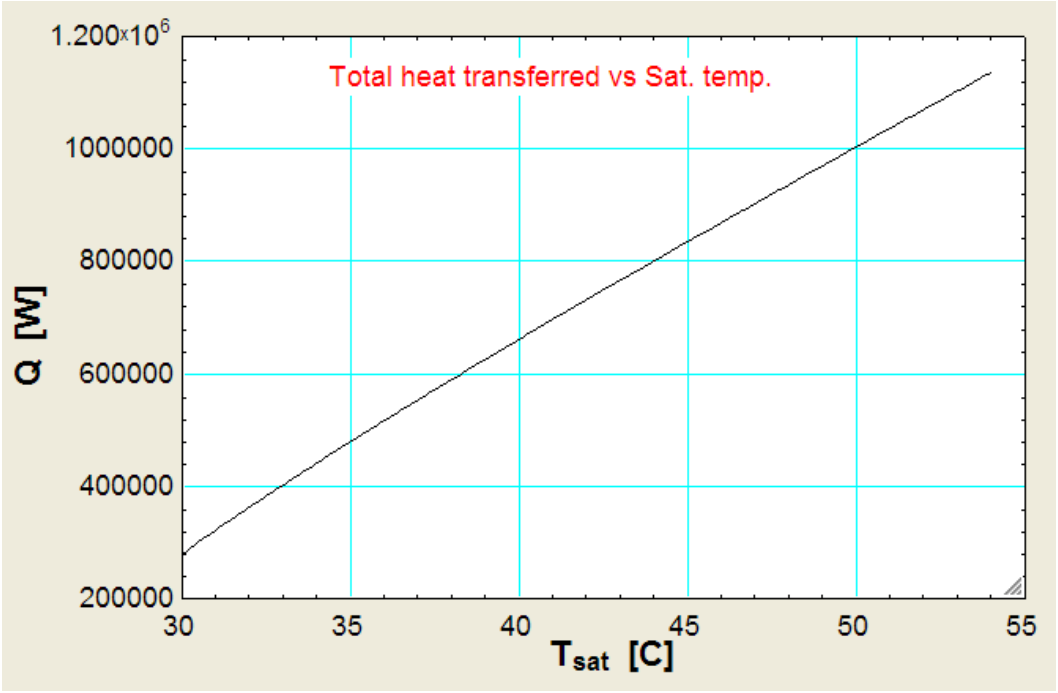
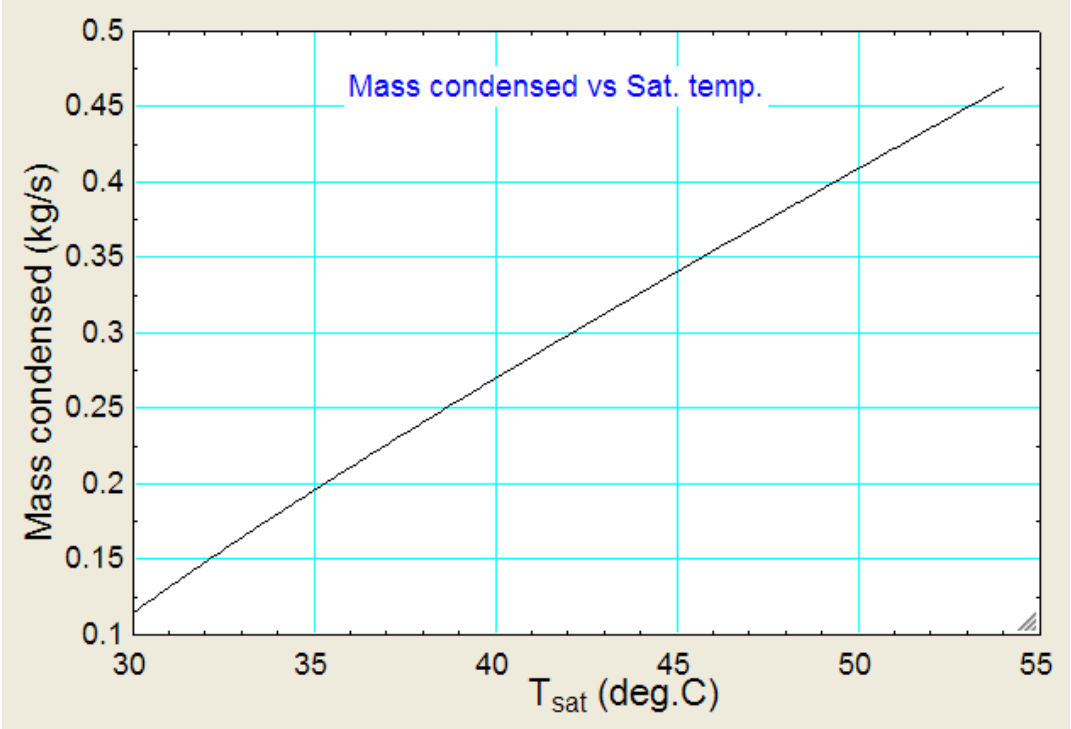
**Now, plot the results:**




==========

**Prob. 3.2.20.** Refrigerant 12 (R12) at 35 C is to be condensed at the rate of 10000 kg/h on a square array of 25 × 25 tubes, each tube of 12 mm OD, maintained at 25 C. Calculate the length of each tube required.

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**EES Solution:**

**Use the EES procedure for a Tube bank:**

**"Data:"**

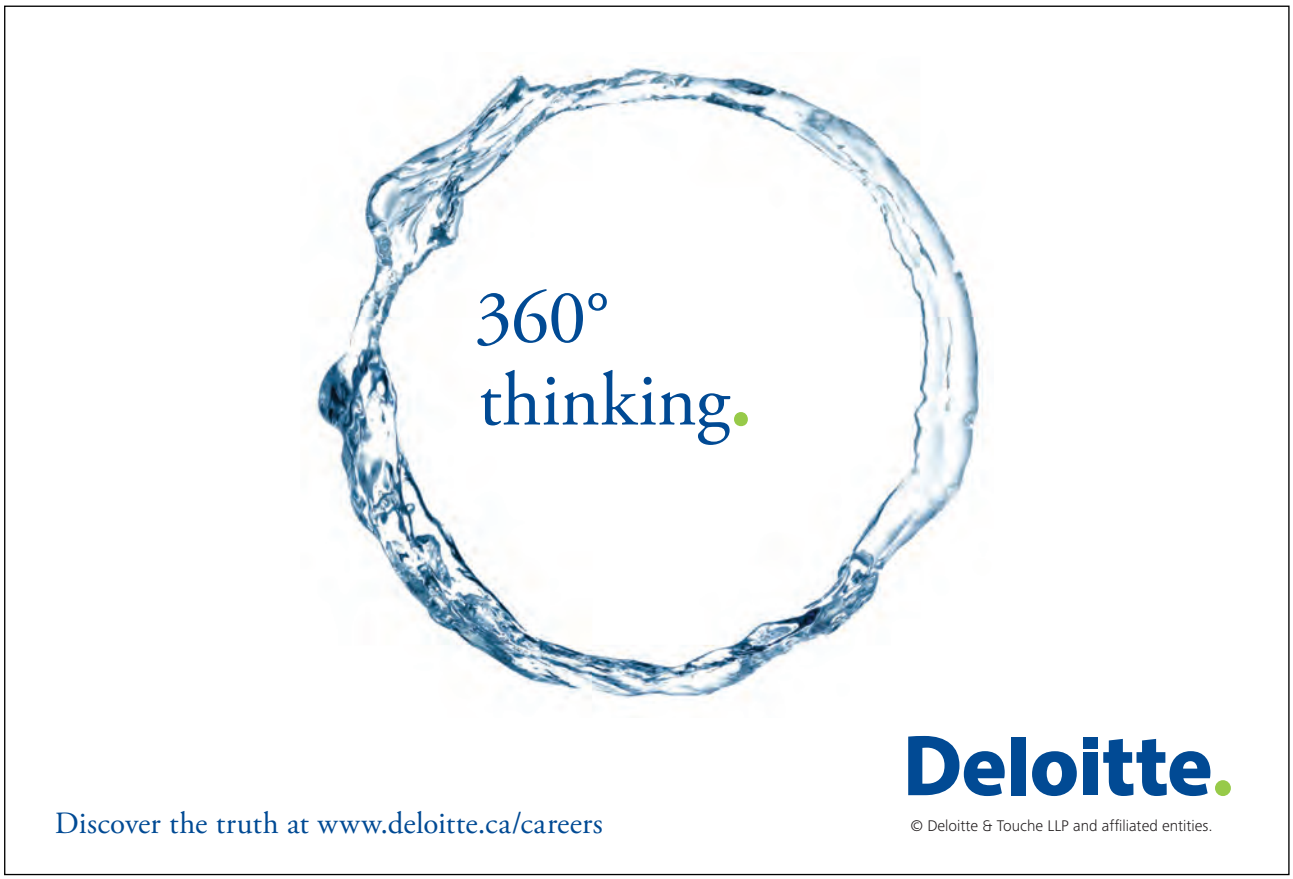
T_sat = 35 [C]
T_s = 25 [C]
D = 0.012 [m]
N_total = 625

N = 25 "i.e. N = 400^0.5, since there are 400 tubes in a square array."

mass_condensed = 10000 * convert(kg/h, kg/s)

Fluid$ = 'R12'

CALL condensation_HTBank_Fluid(Fluid$,T_sat, T_s, D, L, N, N_total: h_avg, Q, mass_condensed)

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**Click on F2 to solve, and we get:**

Main | condensation_HTBank_Fluid

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| D = 0.012 [m] | Fluid$ = 'R12' | $h_{avg}$ = 738.5 [W/m$^2$-C] |
| L = 2.211 [m] | $mass_{condensed}$ = 2.778 [kg/s] | N = 25 |
| $N_{total}$ = 625 | Q = 384719 [W] | $T_s$ = 25 [C] |
| $T_{sat}$ = 35 [C] | | |

Main | condensation_HTBank_Fluid

**Local variables in Procedure condensation_HTBank_Fluid (3 calls, 0.06 sec)**

| | | |
|---|---|---|
| $cp_l$ =969.4 [J/kg-C] | D =0.012 [m] | Fluid$='R12' |
| g=9.81 [m/s$^2$] | $h_{avg}$ =738.5 [W/m$^2$-C] | $h_f$ =69535 [J/kg] |
| $h_{fg}$ =131907 [J/kg] | $h_{fg'}$ =138499 [J/kg] | $h_g$=201442 [J/kg] |
| $k_l$ =0.06732 [W/m-C] | L=2.211 [m] | $mass_{condensed}$ =2.778 [kg/s] |
| $\mu_l$ =0.0002109 [kg/m-s] | N =25 | $\nu_l$ =1.632E-07 [m$^2$/s] |
| $N_{total}$ =625 | Pr$_F$=3.037 | Q =384719 [W] |
| $\rho_l$ =1292 [kg/m$^3$] | $\rho_v$=48.43 [kg/m$^3$] | $T_f$=30 [C] |
| $T_s$=25 [C] | $T_{sat}$ =35 [C] | |

==========

**Prob. 3.2.21.** Ammonia at 40 C is condensing inside a horizontal tube of 16 mm ID. Mass velocity of ammonia vapour at inlet is 20 kg/(m$^2$.s). Surface of the tube is maintained at a constant temperature of 20 C by circulating cold water. Calculate the fraction of vapour that will condense if the tube is 0.5 m long.(Ref.1)

**EES Solution:**

This is the case of condensation inside a horizontal tube.

Chato's relation is valid for Re_vap < 35000. See the formulas at the beginning of the Chapter.

See the EES Procedure for condensation inside a horizontal tube for any Fluid, written earlier:

Following is the worksheet:

**"Data:"**

T_sat = 40 [C
T_s = 20 [C]
L = 0.5 [m]
D = 0.016 [m]

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```
Fluid$ = 'Ammonia'

G = 20 [kg/m^2-s] "….mass velocity of NH3"

A_c = pi * d^2 / 4 "[m^2]…..area of cross-section of tube"

rho_v = Density(Fluid$,T=T_sat, x=1) "[kg/m^3]"

mu_v = Viscosity(Fluid$,T=T_sat,x=1) "[kg/m-s]"

U_v = G /rho_v "[m/s]…velocity of NH3 vap."

{Re_v = G D / mu_v}

CALL condensation_InsideHCyl(Fluid$,T_sat, T_s, D, L, U_v: h_avg, Q, mass_condensed)

mass_in = G * A_c "[kg/s] … mass flow rate of vap at inlet"

Fraction = mass_condensed / mass_in "….Fraction of vapour condensed"
```

---

Click F2 to solve, and we get:

Main | condensation_InsideHCyl

**Unit Settings: SI C Pa J mass deg**

| | | |
|---|---|---|
| $A_c$ = 0.0002011 [$m^2$] | D = 0.016 [m] | Fluid$ = 'Ammonia' |
| Fraction = 0.6122 | G = 20 [$kg/m^2$-s] | $h_{avg}$ = 5562 [$W/m^2$-C] |
| L = 0.5 [m] | $mass_{condensed}$ = 0.002462 [kg/s] | $mass_{in}$ = 0.004021 [kg/s] |
| $\mu_v$ = 0.00001033 [kg/m-s] | Q = 2796 [W] | $\rho_v$ = 12.02 [$kg/m^3$] |
| $T_s$ = 20 [C] | $T_{sat}$ = 40 [C] | $U_v$ = 1.663 [m/s] |

Main | condensation_InsideHCyl

**Local variables in Procedure condensation_InsideHCyl (1 call, 0.02 sec)**

| | | |
|---|---|---|
| $cp_l$ =4827 [J/kg-C] | D =0.016 [m] | Fluid$='Ammonia' |
| g=9.81 [$m/s^2$] | $h_{avg}$ =5562 [$W/m^2$-C] | $h_f$ =390639 [J/kg] |
| $h_{fg}$ =1.099E+06 [J/kg] | $h_{fg'}$ =1.136E+06 [J/kg] | $h_g$=1.490E+06 [J/kg] |
| $k_l$ =0.4714 [W/m-C] | L=0.5 [m] | $mass_{condensed}$ =0.002462 [kg/s] |
| $\mu_l$ =0.0001255 [kg/m-s] | $\mu_v$=0.00001033 [kg/m-s] | $\nu_l$ =2.109E-07 [$m^2/s$] |
| $Pr_f$1.285 | Q =2796 [W] | $Re_{vap}$=30991 |
| $\rho_l$ =595.3 [$kg/m^3$] | $\rho_v$=12.02 [$kg/m^3$] | $T_f$=30 [C] |
| $T_s$=20 [C] | $T_{sat}$ =40 [C] | $U_v$ =1.663 [m/s] |

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**Thus:**

**h_avg = 5562 W/m^2.C ….Ans.**

**Q = 2796 W …. Ans.**

**Mass_cond = 0.002462 kg/s …. Ans.**

**Mass_in = 0.004021 kg/s**

**Therefore, fraction of Mass condensed:**

**Fraction = 0.6122 = 61.22 % …. Ans.**

==========

**Prob. 3.2.22.** Sat.steam at 1 atm condenses on a 0.5 m high, 0.2 m wide vertical plate maintained at 90 C. Determine: (a) the thickness of film at the bottom of the plate, delta_L, (b) film Reynolds No. Re_f, (c) heat transfer coeff. h_avg, (d) total heat transfer, Q, and (e) the condensation rate.

**EXCEL Solution:**

Let us solve this problem in EXCEL.

We have already written VBA Functions for the properties of sat. water, air etc. and we shall use the same worksheet.

Following are the steps:

1. Set up the EXCEL worksheet, enter data and name the cells:

T_f =(T_s +T_sat)/2

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 209 | | | | | | |
| 210 | | Data: | Fluid = | Water | | |
| 211 | | Surface temp | T_s | 90 | C | |
| 212 | | Sat. temp. | T_sat | 100.0 | C | |
| 213 | | Avg. temp | T_f | 95.0 | C | |
| 214 | | Height of plate | L | 0.5 | m | |
| 215 | | Width of plate | B | 0.2 | m | |
| 216 | | Inclination to vertical | theta | 0.0 | deg. | |
| 217 | | Accn. due to gravity | g | 9.810 | m/s^2 | |

$T\_f = (T\_s + T\_sat)/2$

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2. Calculate the properties of water, using the VBA Functions already writte. Note that liquid properties are determined at the mean temp, T_f and heat of vapourization h_fg and properties of vapour are determined at the sat. temp T_sat:

h_fg =SatH2O_hfg_T((T_sat+273.15))

| | A | B | C | D | E | F | G |
|---|---|---|---|---|---|---|---|
| 221 | | **Calculations:** | | | | | |
| 222 | | **Props. of liquid.. at Tf:** | | | | | |
| 223 | | density_liq | **rho_L** | **961.6401735** | kg/m^3 | | |
| 224 | | dyn. Visc_liq | **mu_L** | **0.000295** | N.s/m^2 | | |
| 225 | | kinem. Visc. of liq | **nu_L** | **3.07069E-07** | m^2/s | | |
| 226 | | th. conductivity_liq | **k_L** | **0.67826** | W/m.C | | |
| 227 | | sp.heat_liq | **cp_L** | **4212.15** | J/kg.K | | |
| 228 | | Prandtl No._liq | **Pr_L** | **1.8407** | | | |
| 229 | | | | | | | |
| 230 | | | | | | | |
| 231 | | **Props of vapour: at Tsat:** | | | | | |
| 232 | | density_vap | **rho_V** | **0.5956** | kg/m^3 | | |
| 233 | | sp.heat_vap | **cp_V** | **2029** | J/kg.K | | |
| 234 | | th. conductivity_vap | **k_V** | **0.0248** | W/m.C | | |
| 235 | | Heat of vaporization | **h_fg** | **2257000** | J/kg | | |
| 236 | | Modified h_fg | **h_fg_prime** | **2285642.62** | J/kg | | |
| 237 | | | | | | | |

Using VBA Functions for Props. of Sat. water

$h\_fg\_prime = h\_fg + 0.68 * cp\_L * (T\_sat - T\_s)$

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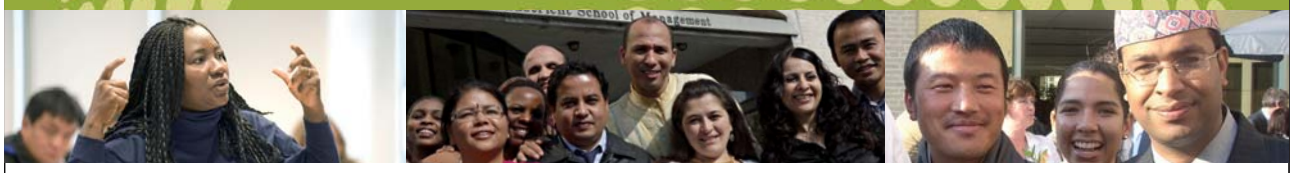

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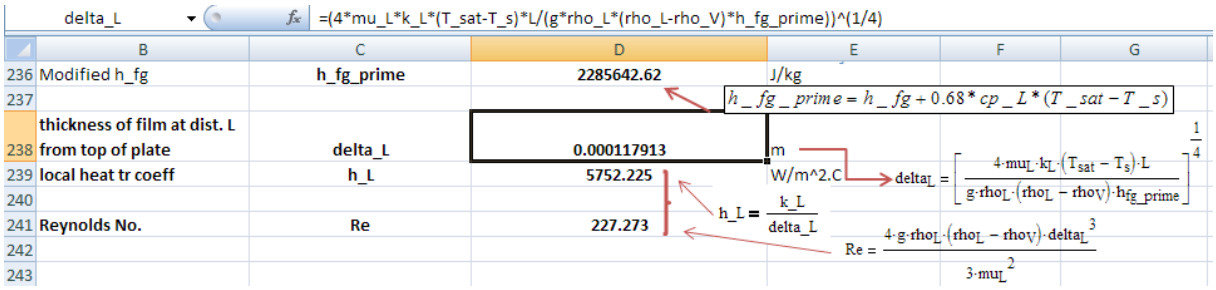
3. Now, continue the calculations to find thickness of condensate film at the lower end of plate, i.e. at x = L, (delta_L), local heat transfer coeff. h_L at x = L, and the film Reynplds No. (Re), as shown below. Equations used are also shown in the worksheet, for clarity:


delta_L
=(4*mu_L*k_L*(T_sat-T_s)*L/(g*rho_L*(rho_L-rho_V)*h_fg_prime))^(1/4)
B C D E F G
236 Modified h_fg h_fg_prime 2285642.62 J/kg
237
238 thickness of film at dist. L from top of plate delta_L 0.000117913 m
239 local heat tr coeff h_L 5752.225 W/m^2.C
240
241 Reynolds No. Re 227.273
242
243
h_fg_prime = h_fg + 0.68 * cp_L * (T_sat − T_s)
delta_L = [4·mu_L·k_L·(T_sat − T_s)·L / g·rho_L·(rho_L − rho_V)·h_fg_prime]^(1/4)
h_L = k_L / delta_L
Re = 4·g·rho_L·(rho_L − rho_V)·delta_L^3 / 3·mu_L^2

4. Re calculated above indicates the if the film is laminar, laminar-wavy, or turbulent. Equations for the average heat transfer coeff, h_vert, in three types of flow are given at the beginning of the Chapter and are reproduced below. These values are calculated separately and kept ready, and the appropriate value is chosen depending on value of Re, using an IF Function in EXCEL:

**For Laminar film: (i.e. 0 < Re <= 30):**

$$h_{vert} = 1.47 \cdot Re^{\frac{-1}{3}} \cdot k_L \cdot \left(\frac{g}{\nu_L^2}\right)^{\frac{1}{3}} \quad \text{if } 0 < Re \le 30$$

---

**For Laminar-wavy film: (i.e. 30 < Re <= 1800):**

$$h_{vert} = \frac{Re \cdot k_L}{1.08 \cdot Re^{1.22} - 5.2} \cdot \left(\frac{g}{\nu_L^2}\right)^{\frac{1}{3}}$$

$$Re_f = \left[4.81 + \frac{3.7 \cdot L \cdot k_L \cdot (T_{sat} - T_s)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^2}\right)^{\frac{1}{3}}\right]^{0.82}$$

---

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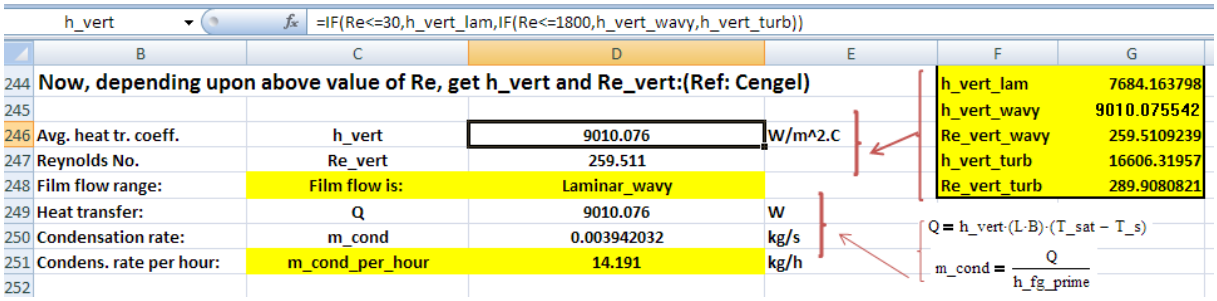
**For turbulent film: (i.e. Re > 1800):**

$$h_{vert} = \frac{Re \cdot k_L}{8750 + 58 \cdot Pr_L^{-0.5} \cdot \left(Re^{0.75} - 253\right)} \cdot \left(\frac{g}{\nu_L^2}\right)^{\frac{1}{3}}$$

$$Re_f = \left[\frac{0.069 L \cdot k_L \cdot Pr_L^{0.5} \cdot \left(T_{sat} - T_s\right)}{mu_L \cdot h_{fg\_prime}} \cdot \left(\frac{g}{\nu_L^2}\right)^{\frac{1}{3}} - 151 \cdot Pr_L^{0.5} + 253\right]^{\frac{4}{3}}$$

---




In the above, yellow-filled box at the right corner calculates the values of h_vert separately and the cells are 'named'. Then, actual values of h_vert and Re_vert are transferred to cells D246 and D247 using the IF Function. Formula of IF Function entered in cell D246 can be seen in the Formula bar.

5. Thus, the results are:

**delta_L = 0.000117913 m…. thickness of condensate film at the bottom of plate (i.e. at x = 0.5 m)**

**Re_f = 259.511 = Reynolds No. …Laminar wavy region**

**h_avg = h_vert = 9010.1 W/m^2.C = avg heat transfer coeff**

**Q = 9010.71 W = heat tr to plate**

**m_cond = 0.003942 kg/s = 14.191 kg/h ….Ans.**

---

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6. **If the plate is inclined to vertical at 30 deg. what are the changes in results?**

For an inclined plate, inclined at an angle of **θ** deg. to vertical, we have:

**h_inclined = h_vert x (cos(θ))^(1/4)**

Following worksheet shows these calculations:

D256 =h_vert*(COS(D255))^(1/4)

| | B | C | D | E |
|---|---|---|---|---|
| 250 | Condensation rate: | m_cond | 0.003942032 | kg/s |
| 251 | Condens. rate per hour: | m_cond_per_hour | 14.191 | kg/h |
| 252 | | | | |
| 253 | If the plate is inclined at 'theta' deg. to vertical: | | | |
| 254 | Angle of incln. to vert. | theta | 30 | deg. |
| 255 | theta in radians | theta_rad | 0.523598776 | radians |
| 256 | heat tr coeff. | h_inclined | 8691.827 | W/m^2.C |
| 257 | Heat transfer: | Q_inclined | 8691.827 | W |
| 258 | Condensation rate: | m_cond_incl | 0.003803 | kg/s |
| 259 | Condens. rate per hour: | m_cond_incl_per_hour | 13.690 | kg/h |

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In the above worksheet, note that theta was converted from degrees to radians, since EXCEL requires that arguments to Trigonometric Functions such as Sin, Cos etc. should be in radians.

Thus, we get, for the plate inclined at 30 deg to vertical:

**h_avg = h_inclined = 8691.83 W/m^2.C = avg heat transfer coeff**

**Q_inclined = 8691.83 W = heat tr to inclined plate**

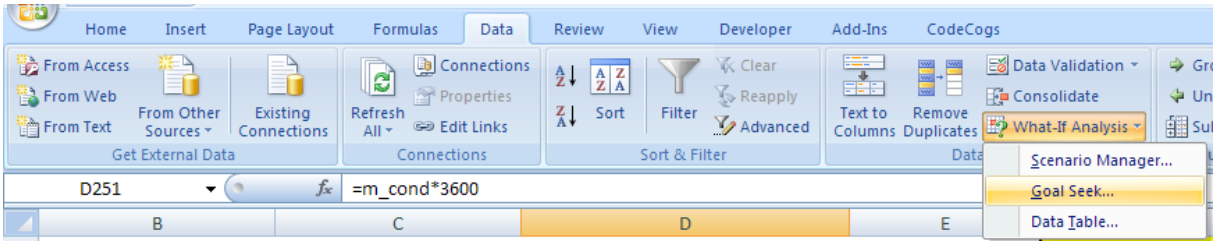
**m_cond_incl = 0.003803 kg/s = 13.69 kg/h ….Ans.**

---

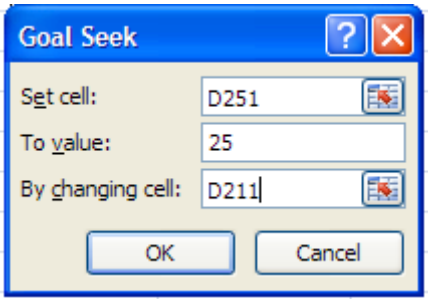
7. **For the vertical plate, what should be the surface temp to achieve a condensation rate of 25 kg/h?**

This is calculated very easily using the Goal Seek in EXCEL. We will apply Goal Seek, to make cell D251 zero, by changing cell D211 (i.e. value of T_s): Following is the procedure:

Select cell D251, and go to Data – WhatIf Analysis – Goal Seek:




Click on Goal Seek. We get the following screen. Fill it up as explained above:

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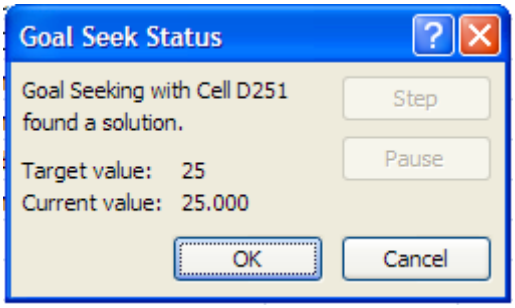
Press OK. We get:




i.e. Goal Seek has found a solution. Again click OK and see the value of T_s in cell D211:

| | | | | |
|---|---|---|---|---|
| 210 | Data: | Fluid = | Water | |
| 211 | Surface temp | T_s | 79.3601 | C |
| 212 | Sat. temp. | T_sat | 100.0 | C |
| 213 | Avg. temp | T_f | 89.7 | C |
| 214 | Height of plate | L | 0.5 | m |
| 215 | Width of plate | B | 0.2 | m |
| 216 | Inclination to vertical | theta | 0.0 | deg. |
| 217 | Accn. due to gravity | g | 9.810 | m/s^2 |

$T\_f = (T\_s + T\_sat)/2$

Thus:

**Surface temp required to get a cond. rate of 25 kg/h is: T_s = 79.3601 deg. C….Ans.**

---

8. **Now, plot the surface temps for different condensation rates (from 15 to 50 kg/h):**

Here, we have to apply Goal Seek to each value of m_cond. So, it is convenient to write a small VBA program:

First, set up a Table as shown below:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 262 | | Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h: | | | |
| 263 | | | m_cond-starting value = m_initial | 10 | kg/h |
| 264 | | | m_cond_final value = m_final | 50 | ...upper limit is 65 kg/h |
| 265 | | | Change these two values between 0 and 65 and click CommandButton1 | | |
| 266 | | | | | |
| 267 | | m_cond (kg/h) | h_vert (W/m^2.C) | Q (W) | T_s (deg.C) |
| 268 | | | | | |
| 269 | | | | | |
| 270 | | | | | |
| 271 | | | | | |
| 272 | | | | | |
| 273 | | | | | |
| 274 | | | | | |
| 275 | | | | | |
| 276 | | | | | |

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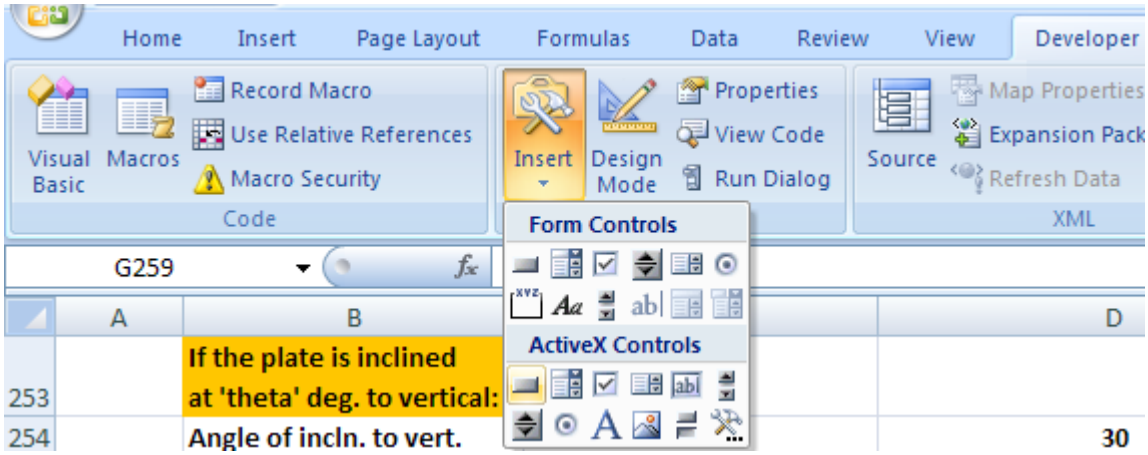
Here, we enter the range of m_cond desired in cells D263 and D264 as shown.

Table has 9 rows; so increment will be: Inc = (final value – initial value) / 8 = 5

Now, we will have a control button to operate our VBA program.

So, go to: Developer – Insert – ActiveX controls:



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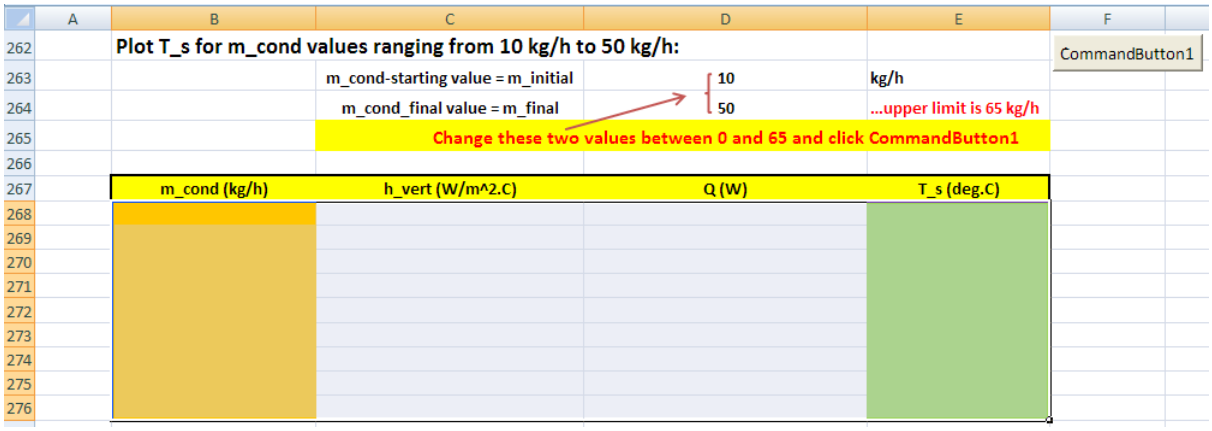
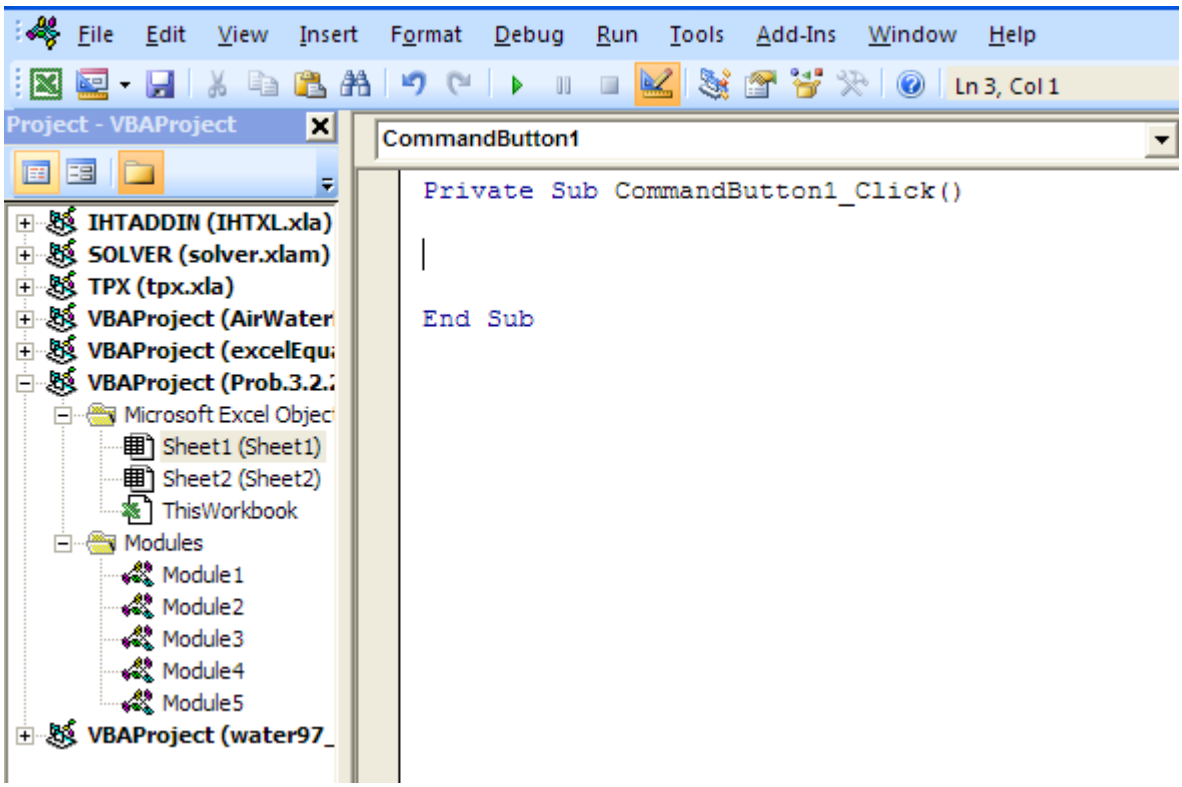
Click on first, left button under ActiveX Controls, and locate the button at the required place in the worksheet and adjust its size:




Now, in Developer tab, click VisualBasic (extreme left) and we see under Sheet 1, the VBA program for this control button:

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Now, modify this program to:

generate the value of m_cond within the desired range and apply Goal Seek, get the values of h, Q and T_s for each case, and write them all at appropriate places in the Table.

Following is the program:

CommandButton1 | Click

```
Private Sub CommandButton1_Click()

Dim i As Integer
Dim m_initial As Double, m_final As Double, Inc As Double

m_initial = Range("D263") 'starting value for m_cond
m_final = Range("D264") 'starting value for m_cond

Inc = (m_final - m_initial) / 8

For i = 0 To 8

Range("D251").GoalSeek Goal:=m_initial + i * Inc, ChangingCell:=Range("D211") 'This line performs Goal Seek

Cells(268 + i, 2) = m_initial + i * Inc 'Fills the first column of Table, i.e. m_cond values

Cells(268 + i, 3) = Range("D246") 'Fills the second column of Table, i.e. h_vert values

Cells(268 + i, 4) = Range("D249") 'Fills the third column of Table, i.e. Q values

Cells(268 + i, 5) = Range("D211") 'Fills the fourth column of Table, i.e. T_s values

Next i

End Sub
```

In the above program, read the comments given to see what each line does.

Now, click on the CommandButton1 and we get:

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 262 | | Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h: | | | | CommandButton1 |
| 263 | | | m_cond-starting value = m_initial | 10 | kg/h | |
| 264 | | | m_cond_final value = m_final | 50 | ...upper limit is 65 kg/h | |
| 265 | | | Change these two values between 0 and 65 and click CommandButton1 | | | |
| 266 | | | | | | |
| 267 | | m_cond (kg/h) | h_vert (W/m^2.C) | Q (W) | T_s (deg.C) | |
| 268 | | 10 | 9785.894 | 6320.857 | 93.541 | |
| 269 | | 15 | 8890.174 | 9532.118 | 89.278 | |
| 270 | | 20 | 8275.042 | 12784.572 | 84.550 | |
| 271 | | 25 | 7792.478 | 16083.592 | 79.360 | |
| 272 | | 30 | 7392.308 | 19434.487 | 73.710 | |
| 273 | | 35 | 7040.901 | 22844.055 | 67.555 | |
| 274 | | 40 | 6718.590 | 26320.306 | 60.825 | |
| 275 | | 45 | 6411.791 | 29873.807 | 53.408 | |
| 276 | | 50 | 6139.606 | 33507.805 | 45.424 | |

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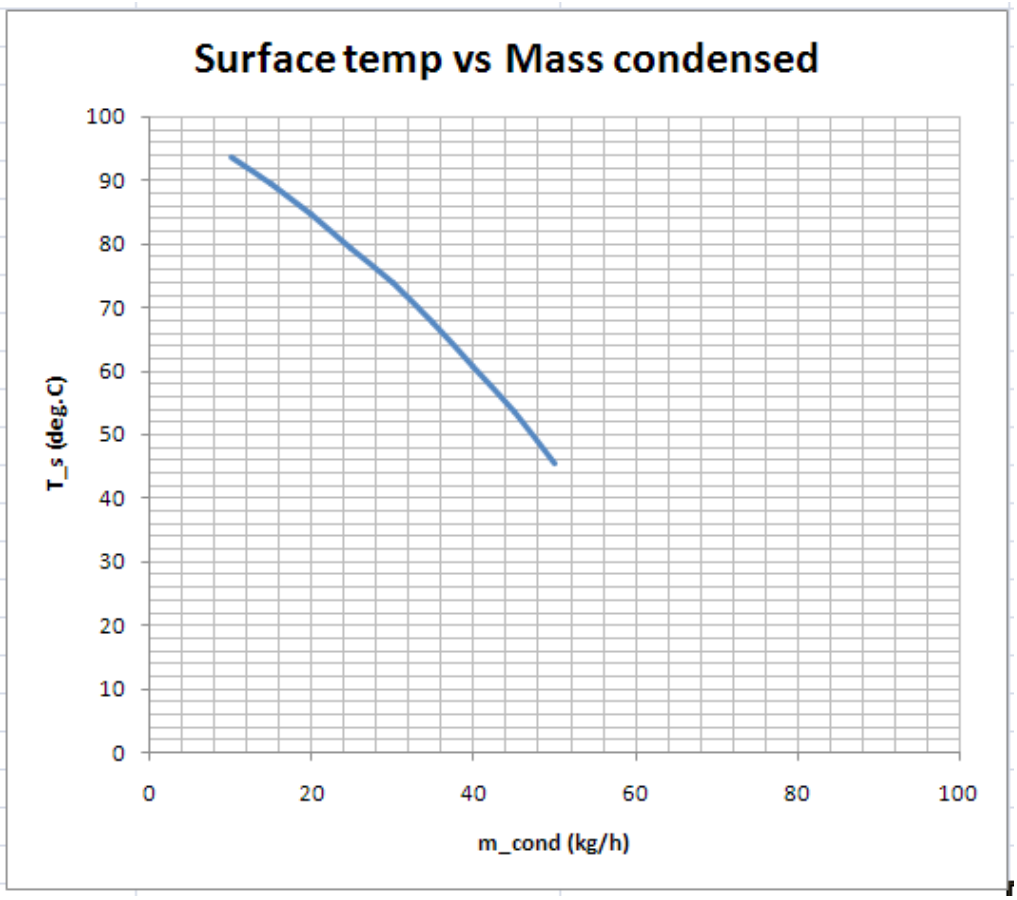
Now, plot the graph:




9. Now, if we need the T_s values for another range of mass_condensed, we have to just enter the desired values in cells D263 and D264 and click the CommandButton1. ***But, take care to see that upper limit for mass condensed should not go beyond 65 kg/h, since otherwise, T_s value will go below zero and the program will stop.***

For ex: let us have m_cond between 0 and 65 kg/h:

Then, enter the values in D263 and D264 as shown and click CommandButton1. We get:

Plot T_s for m_cond values ranging from 10 kg/h to 50 kg/h:

CommandButton1

| | | | |
|---|---|---|---|
| | m_cond-starting value = m_initial | 0 | kg/h |
| | m_cond_final value = m_final | 65 | ...upper limit is 65 kg/h |

Change these two values between 0 and 65 and click CommandButton1

| m_cond (kg/h) | h_vert (W/m^2.C) | Q (W) | T_s (deg.C) |
|---|---|---|---|
| 0 | 2093998.422 | 0.000 | 100.000 |
| 8.125 | 10262.297 | 5126.234 | 95.005 |
| 16.25 | 8717.986 | 10341.175 | 88.138 |
| 24.375 | 7847.619 | 15668.487 | 80.034 |
| 32.5 | 7210.868 | 21131.604 | 70.695 |
| 40.625 | 6678.726 | 26760.200 | 59.932 |
| 48.75 | 6205.622 | 32591.079 | 47.481 |
| 56.875 | 5630.841 | 38753.608 | 31.176 |
| 65 | 5001.528 | 45414.907 | 9.198 |

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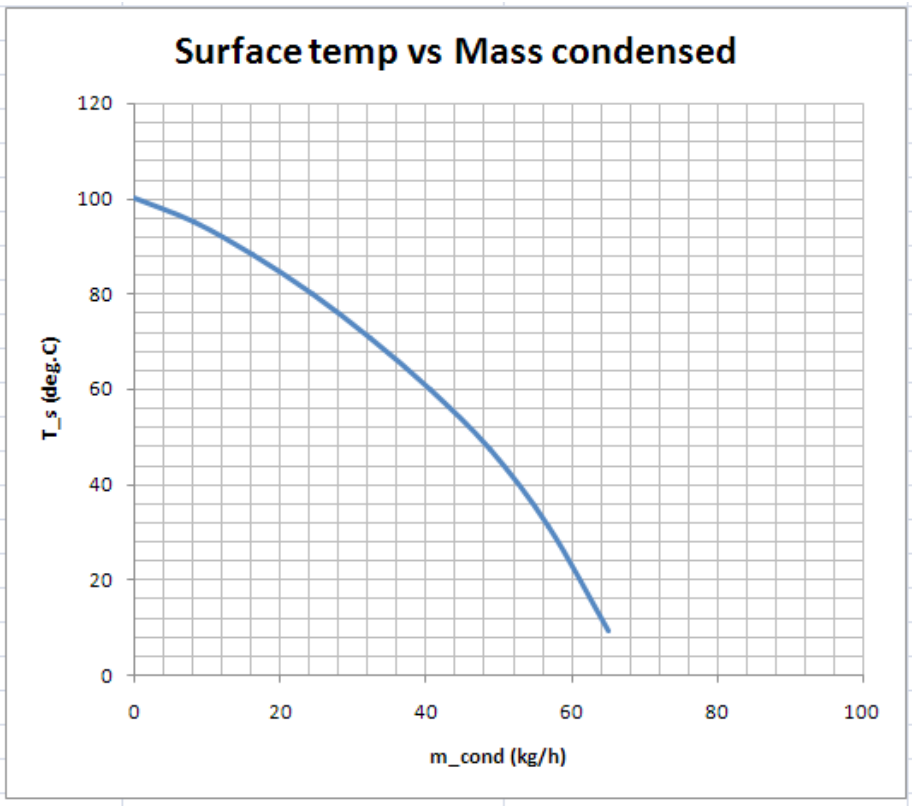
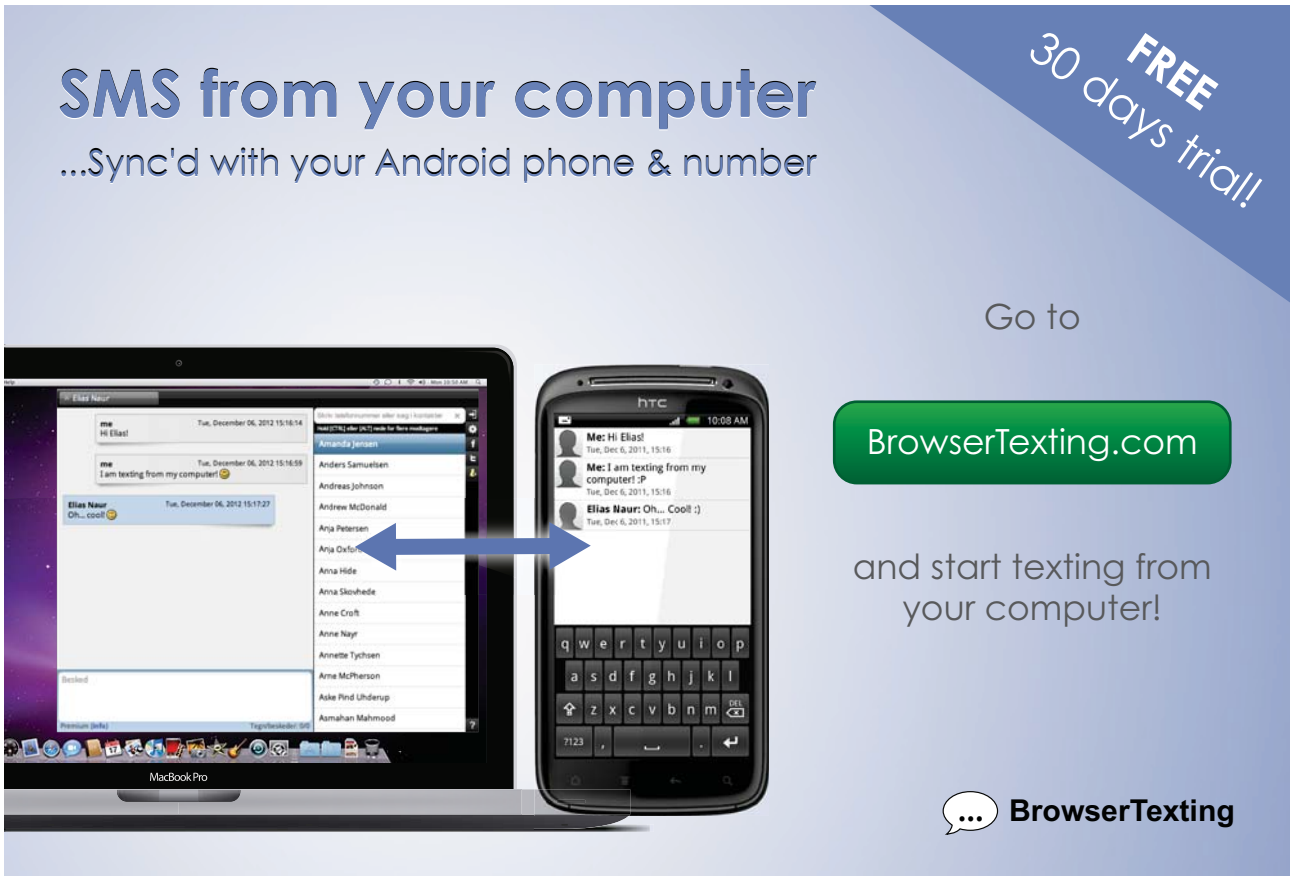
And, the plot immediately changes as follows:




==========

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**Note:** While solving this problem, all the calculations have been done in the worksheet itself. So, values of all steps are seen transparently in the worksheet. For example, as the T_s changes how all values, including properties of Water, change can be seen in the worksheet.

**So, this worksheet can be used as Template for all such condensation calculations on a vertical plate.**

However, if we don't need all the intermediate values, it is better to write a VBA Function to do the calculations and return the desired final values only. This is demonstrated in the next problem:

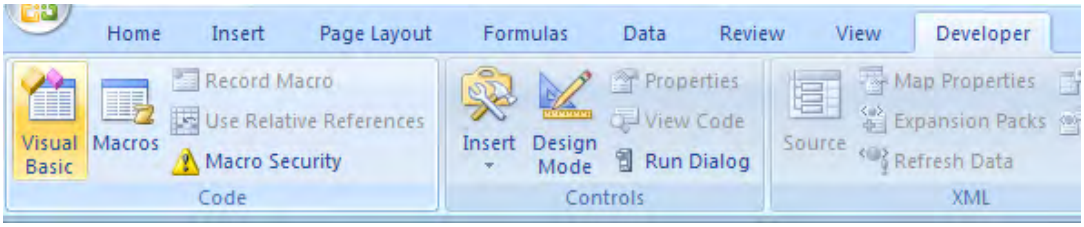
==========

**Prob. 3.2.23.** Solve the above Problem in EXCEL using VBA Function written for the purpose:.

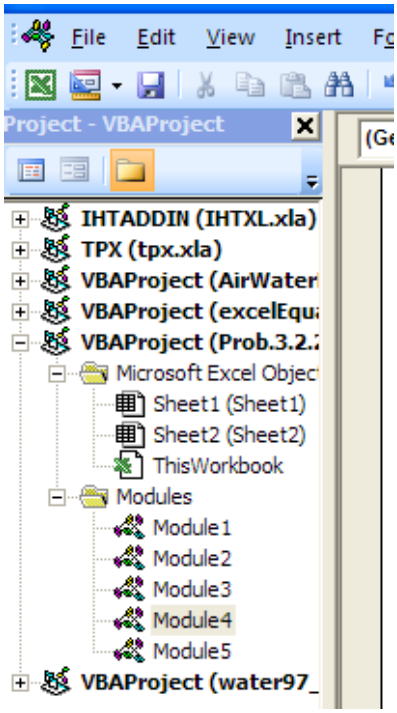
**EXCEL Solution:**

Let us write a VBA Function to do the calculations:

1. In the above Worksheet, go to: Developer – Visual Basic:




Click on Visual Basic, Select Module4:

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And, type the following code:

```
Function Condensation_VPlate_Steam(T_sat As Double, T_s As Double, b As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Vertical Plate  held at T_s

'Calculates h_avg for laminar, wavy and turbulent film condensation
'based on value of Re_f

'Note: positive x direction is from top of plate downwards; y dirn is from left to right
'x is the distance from top, b is the breadth of plate perpendicular to paper

Dim g As Double, Re As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, delta_l As Double, Re_f As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling"
delta_l = ((4 * k_l * mu_l * (T_sat - T_s) * L) / _
(rho_l * (rho_l - rho_v) * g * h_fg_prime)) ^ (1 / 4) '[m]....thickness of film at a
'distance L from top

Re = (4 * g * rho_l * (rho_l - rho_v) * delta_l ^ 3) / (3 * mu_l ^ 2) '...film Reynolds No.
```

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```
If (Re > 0) And (Re <= 30) Then  'laminar film

   h_avg = 1.47 * k_l * Re ^ (-1 / 3) * (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = Re 'Film Reynolds No. for laminar flow

ElseIf (Re > 30) And (Re <= 1800) Then 'wavy - laminar flow in film

      h_avg = ((Re * k_l) / (1.08 * Re ^ 1.22 - 5.2)) * (g / nu_l ^ 2) ^ (1 / 3)

      Re_f = (4.81 + (3.7 * L * k_l * (T_sat - T_s) / (mu_l * h_fg_prime)) * (g / nu_l ^ 2) ^ (1 / 3)) ^ 0.82

ElseIf (Re > 1800) Then    'turb. flow in film

   h_avg = ((Re * k_l) / (8750 + 58 * Pr_l ^ (-0.5) * (Re ^ 0.75 - 253))) * _
   (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = ((0.069 * L * k_l * Pr_l ^ 0.5 * (T_sat - T_s) / (mu_l * h_fg_prime)) * _
   (g / nu_l ^ 2) ^ (1 / 3) - 151 * Pr_l ^ 0.5 + 253) ^ (4 / 3)

End If


Q = h_avg * (b * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s

Condensation_VPlate_Steam = Application.Transpose(Array(delta_l, Re_f, h_avg, Q, m_condensed))


End Function
```

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Note in the definition of the Function that:

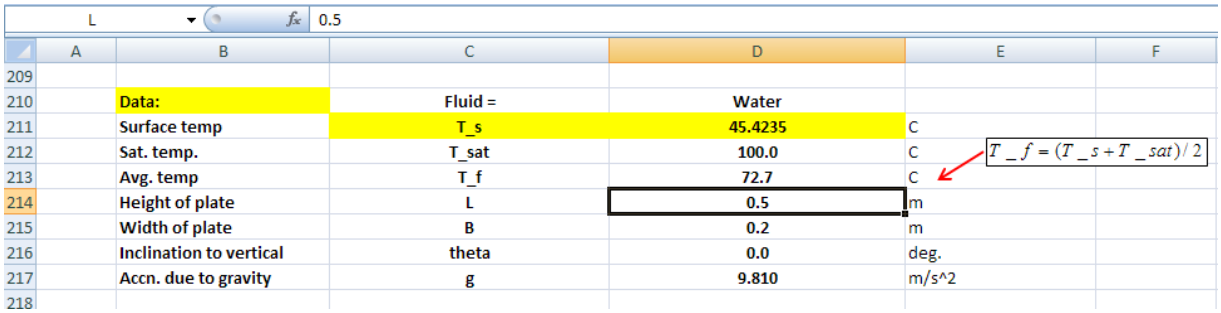
**Inputs are:** T_sat (Sat. temp.), T_s (Surface temp.), b (Width of vertical plate) and L (height of vertical plate)

**Output of Function:** is a vertical array containing, in order: delta_L (thickness of condensate at the bottom of plate), Re_f (film Reynolds No.), h_avg (avg. heat tr coeff. h_vert), Q (heat transfer to the plate in Watts) and m_condensed in kg/s

Now, this Function is available like any other built-in Function in EXCEL.

It is located under the **'User Defined' category**.

Using the earlier Worksheet itself, where the data are entered and the cells are named, we have:




| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 209 | | | | | | |
| 210 | | Data: | Fluid = | Water | | |
| 211 | | Surface temp | T_s | 45.4235 | C | |
| 212 | | Sat. temp. | T_sat | 100.0 | C | |
| 213 | | Avg. temp | T_f | 72.7 | C | |
| 214 | | Height of plate | L | 0.5 | m | |
| 215 | | Width of plate | B | 0.2 | m | |
| 216 | | Inclination to vertical | theta | 0.0 | deg. | |
| 217 | | Accn. due to gravity | g | 9.810 | m/s^2 | |
| 218 | | | | | | |

Now, set up the worksheet with 5 consecutive cells in column C (i.e. cells C308 to C312) selected as shown:

| | A | B | C | D |
|---|---|---|---|---|
| 305 | | | | |
| 306 | | Using the VBA Function for a vertical plate: | | |
| 307 | | | | |
| 308 | | delta_L | | m |
| 309 | | Re_f | | |
| 310 | | h_avg | | W/m^2.C |
| 311 | | Q | | Q |
| 312 | | m_cond | | kg/s |
| 313 | | m_cond_per_hour | | kg/h |
| 314 | | | | |

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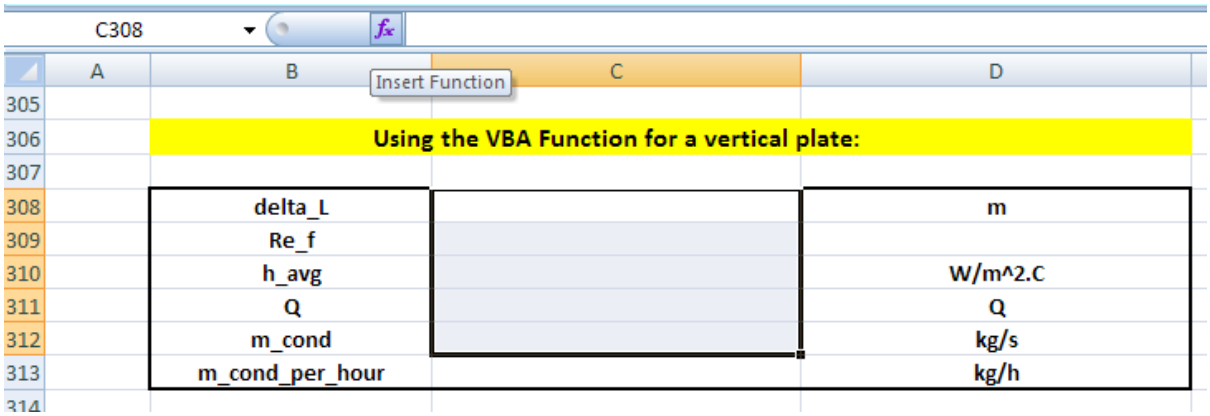
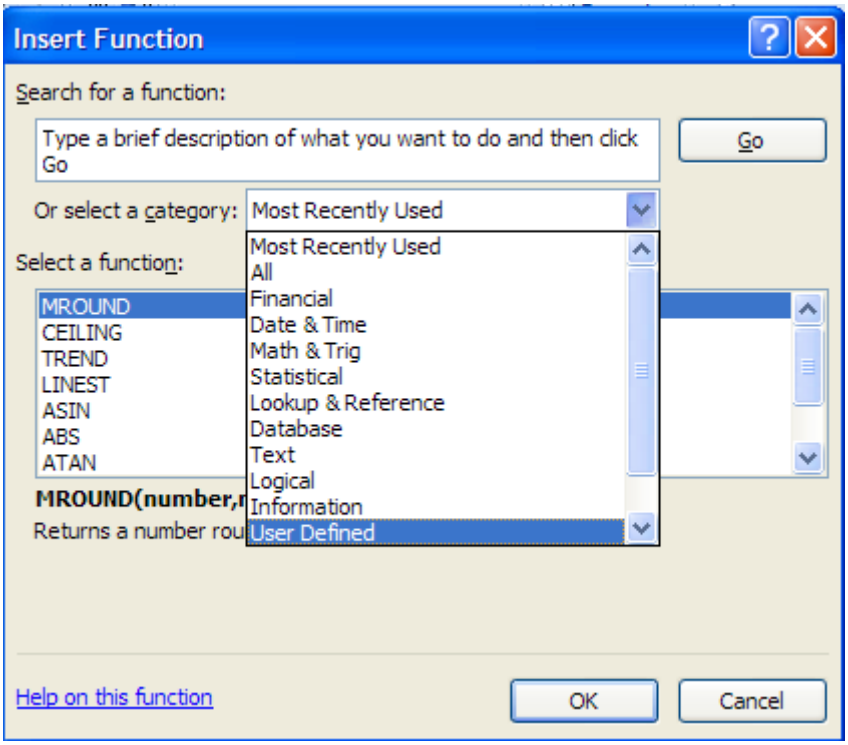
Now, with the range still selected, place the cursor in any cell between C308 and C312, and click on the 'Insert Function' symbol:




Choose 'User Defined' category:




Click OK.

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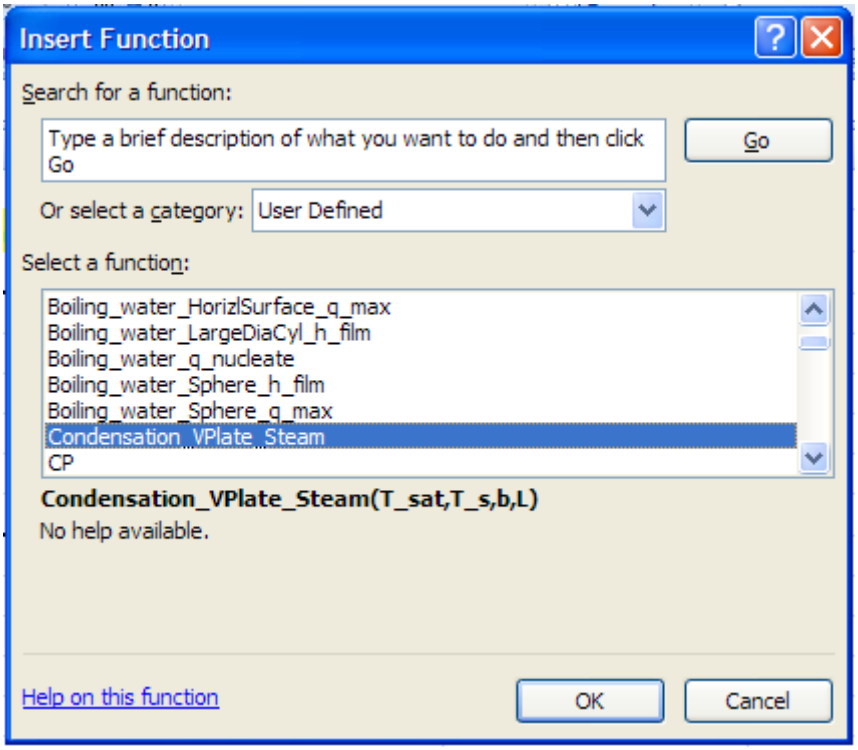
And, in 'Select a Function': click on the desired Function as shown:



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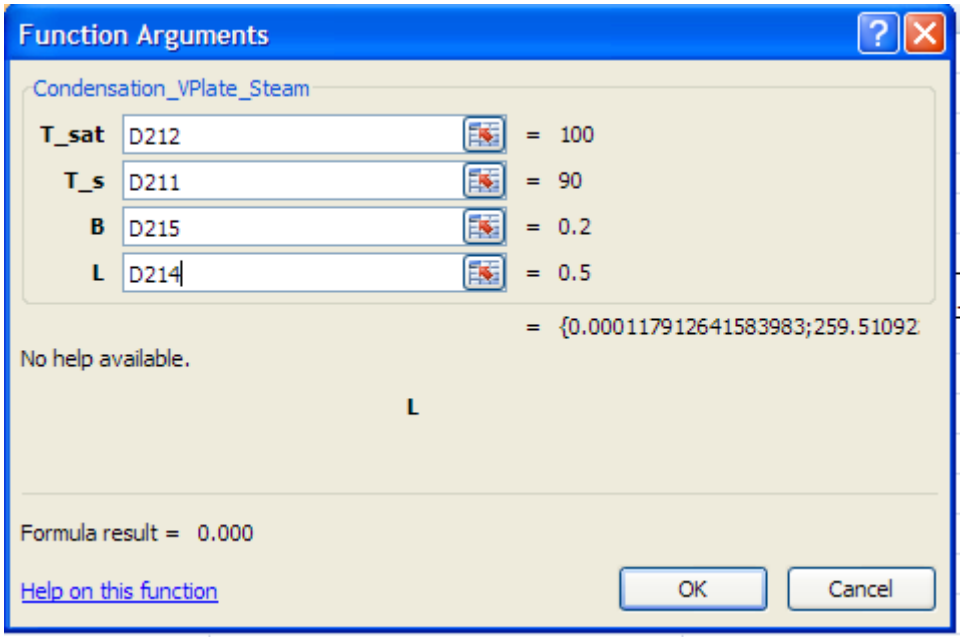
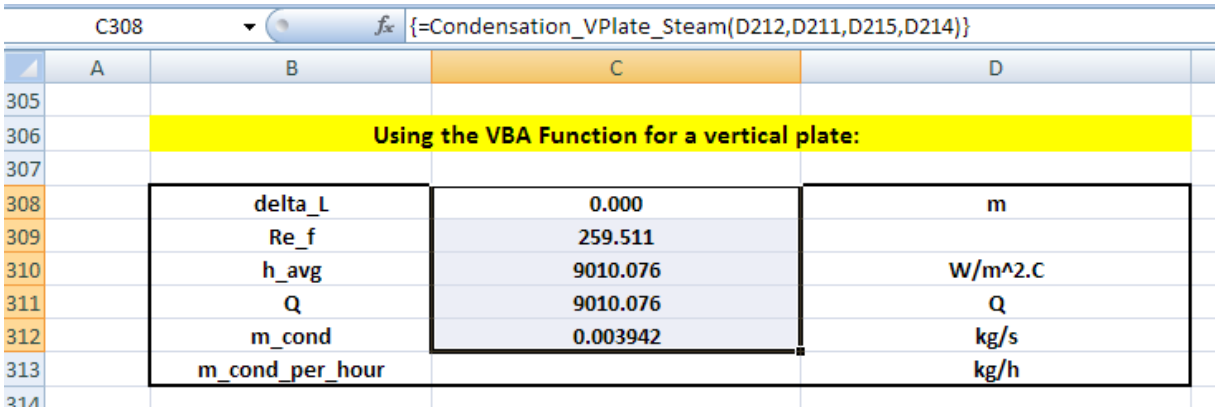
Click OK. We get the following screen. Fill it up as shown:




**Important:** Now, keeping Ctrl+Shift pressed, click OK, since this is an Array Function (i.e. it returns an Array of values).

We get:




Observe that all the 5 selected cells are filled with the respective values returned by the Function.

Last cell, ie. m_cond_per_hour may now be calculated as: m_cond_per_hour = m_cond * 3600.

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Finally, we have:

C313 =C312*3600

| | A | B | C | D |
|---|---|---|---|---|
| 305 | | | | |
| 306 | | Using the VBA Function for a vertical plate: | | |
| 307 | | | | |
| 308 | | delta_L | 0.000 | m |
| 309 | | Re_f | 259.511 | |
| 310 | | h_avg | 9010.076 | W/m^2.C |
| 311 | | Q | 9010.076 | Q |
| 312 | | m_cond | 0.003942 | kg/s |
| 313 | | m_cond_per_hour | 14.191 | kg/h |

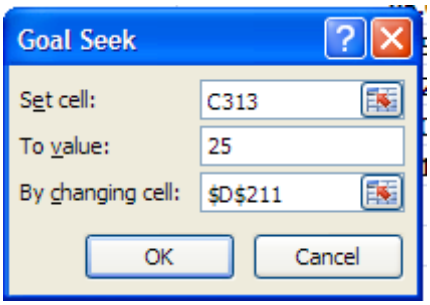
**Note: These values match with those obtained in the previous problem, as they should.**

---

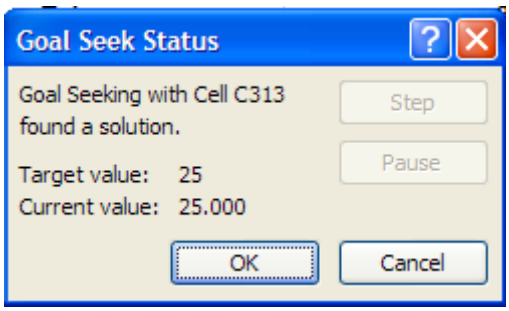
**Now, if we have to find out the T_s required to get a condensation rate of 25 kg/h:**

Apply Goal Seek to make cell C313 equal to 25 by changing cell D211 (i.e. value of T_s).

Applying Goal Seek has been explained in the previous problem. We get:




Click OK. And we get:

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And value of T_s can be seen in cell D211:

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 209 | | | | | | |
| 210 | | Data: | Fluid = | Water | | |
| 211 | | Surface temp | T_s | 79.3601 | C | |
| 212 | | Sat. temp. | T_sat | 100.0 | C | |
| 213 | | Avg. temp | T_f | 89.7 | C | |
| 214 | | Height of plate | L | 0.5 | m | |
| 215 | | Width of plate | B | 0.2 | m | |
| 216 | | Inclination to vertical | theta | 0.0 | deg. | |
| 217 | | Accn. due to gravity | g | 9.810 | m/s^2 | |

$T\_f = (T\_s + T\_sat)/2$

**i.e. Value of T_s required to get a condensation rate of 25 kg/h = 79.36 01deg. C …. Ans.**

*Again, this matches with the value obtained in the previous problem.*

**Thus, we see that using a custom-written VBA Function is advantageous and helps in solving the problems faster and accurately, without having to spend time in entering tedious equations in the cells.**

==========

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**Prob. 3.2.24.** Sat.steam at 1 atm condenses on a 0.3 m high, 1 m wide vertical plate maintained at 90 C. Determine: (a) the thickness of film at the bottom of the plate, delta_L, (b) film Reynolds No. Re_f, (c) heat transfer coeff. h_avg, (d) total heat transfer, Q, and (e) the condensation rate.

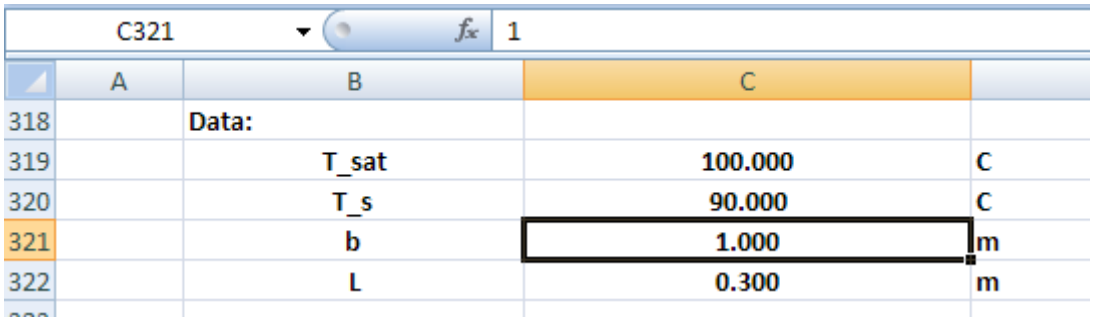
Also, plot the condensation rate for various values of T_s ranging from T_s = 50 C to 90 C.

**EXCEL Solution:**

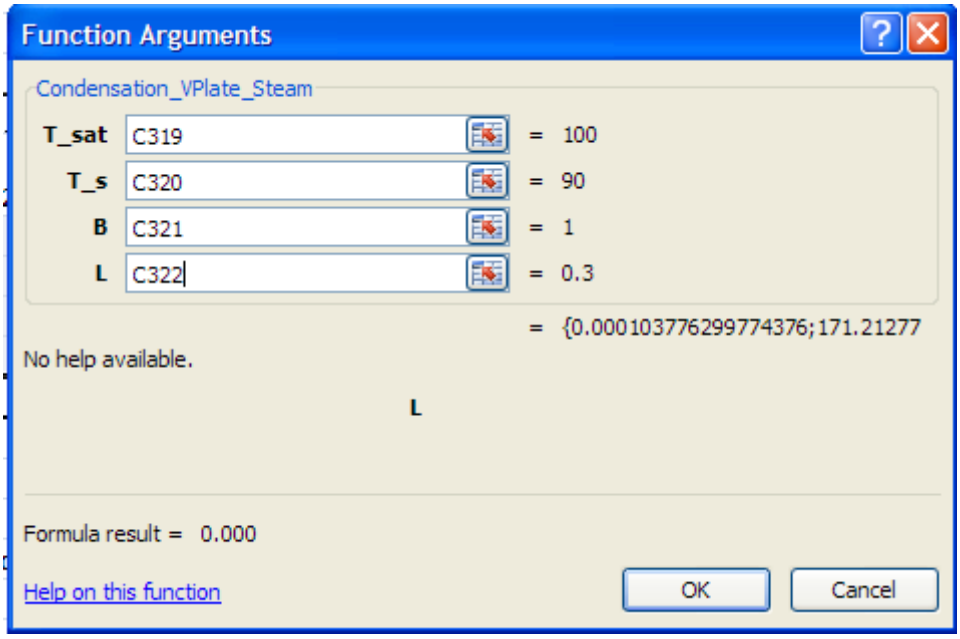
Use the VBA Function for Vertical plate written earlier:

Following are the steps:

1. Set up the worksheet, enter data:




2. Select 5 consecutive cells in column and enter the VBA Function for Condensation on vertical plate as explained in the previous problem.
3. Fill up the arguments of the Function as shown:

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Press (Ctrl + Shift + Enter), since it is an Array Function.

**Results desired are displayed immediately in the selected cells:**

| | A | B | C | D |
|---|---|---|---|---|
| 318 | | Data: | | |
| 319 | | T_sat | 100.000 | C |
| 320 | | T_s | 90.000 | C |
| 321 | | b | 1.000 | m |
| 322 | | L | 0.300 | m |
| 323 | | | | |
| 324 | | delta_L | 0.0001038 | m |
| 325 | | Re_f | 171.213 | |
| 326 | | h_avg | 9840.315 | W/m^2.C |
| 327 | | Q | 29520.944 | W |
| 328 | | m_cond | 0.012916 | kg/s |
| 329 | | m_cond_per_hour | | kg/h |
| 330 | | | | |

4. Now, convert m_cond to m_cond_per_hour by multiplying by 3600:

C329 =C328*3600

| | A | B | C | D |
|---|---|---|---|---|
| 318 | | Data: | | |
| 319 | | T_sat | 100.000 | C |
| 320 | | T_s | 90.000 | C |
| 321 | | b | 1.000 | m |
| 322 | | L | 0.300 | m |
| 323 | | | | |
| 324 | | delta_L | 0.0001038 | m |
| 325 | | Re_f | 171.213 | |
| 326 | | h_avg | 9840.315 | W/m^2.C |
| 327 | | Q | 29520.944 | W |
| 328 | | m_cond | 0.012916 | kg/s |
| 329 | | m_cond_per_hour | 46.497 | kg/h |

**Thus:**

**Condensation rate is: 46.497 kg/h …. Ans.**

---

**To plot m_cond against T_s:**

Let us write a VBA program to do this.

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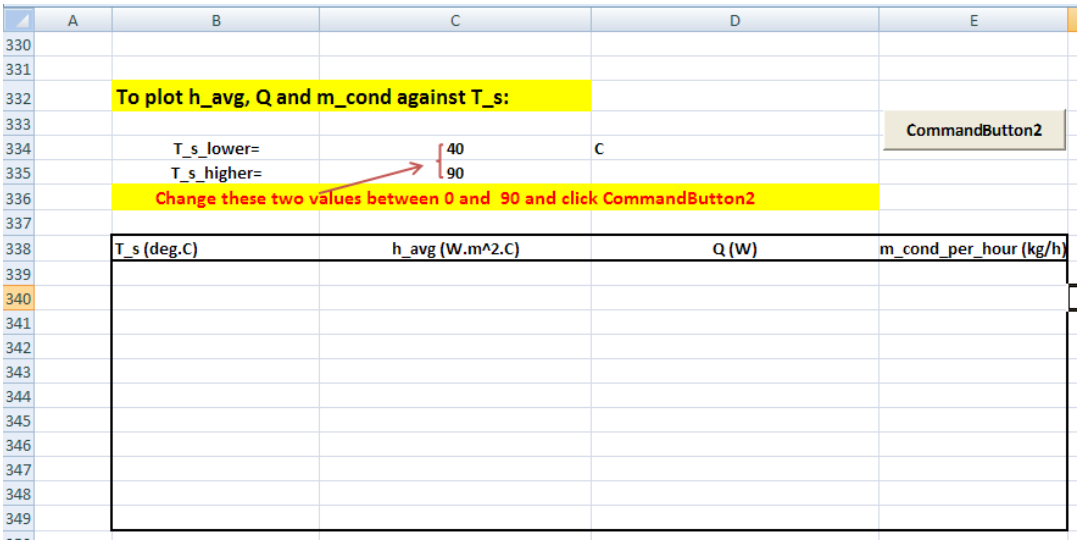
1. Before that, set up a Table as shown:

We plan to give lower limit and upper limit of T_s, and then the program should fill up the Table for 10 equally divided values of T_s and also the program should be executed with a ControlButton.

For the procedure of inserting an ActiveX ControlButton, see the previous problem.

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2. Now, double click on the ControlButton2 and we see the VBA program behind it:

```
Private Sub CommandButton2_Click()

End Sub
```

3. Now, modify this program as follows to perform the desired calculation steps:

```
Private Sub CommandButton2_Click()

Dim i As Integer
Dim T_s_initial As Double, T_s_final As Double, Inc As Double

T_s_initial = Range("C334") 'starting value for T_s
T_s_final = Range("C335") 'starting value for T_s

Inc = (T_s_final - T_s_initial) / 10

For i = 0 To 10

Range("C320") = T_s_initial + i * Inc 'Sets the T_s value to the starting or initial value

'Immediately, all other values will up-date themselves.
'And, copy them to their respective places in the Table:

Cells(339 + i, 2) = Range("C320") 'copies value of T_s to Table
Cells(339 + i, 3) = Range("C326") 'copies value of h_avg to Table
Cells(339 + i, 4) = Range("C327") 'copies value of Q to Table
Cells(339 + i, 5) = Range("C329") 'copies value of m_cond_per_hour to Table


Next i

End Sub
```

Read the comments in the above code to know what each line does.

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4. Now, click on the CommandButton2 and immediately the calculations are done and the Table is filled up:

To plot h_avg, Q and m_cond against T_s:

CommandButton2

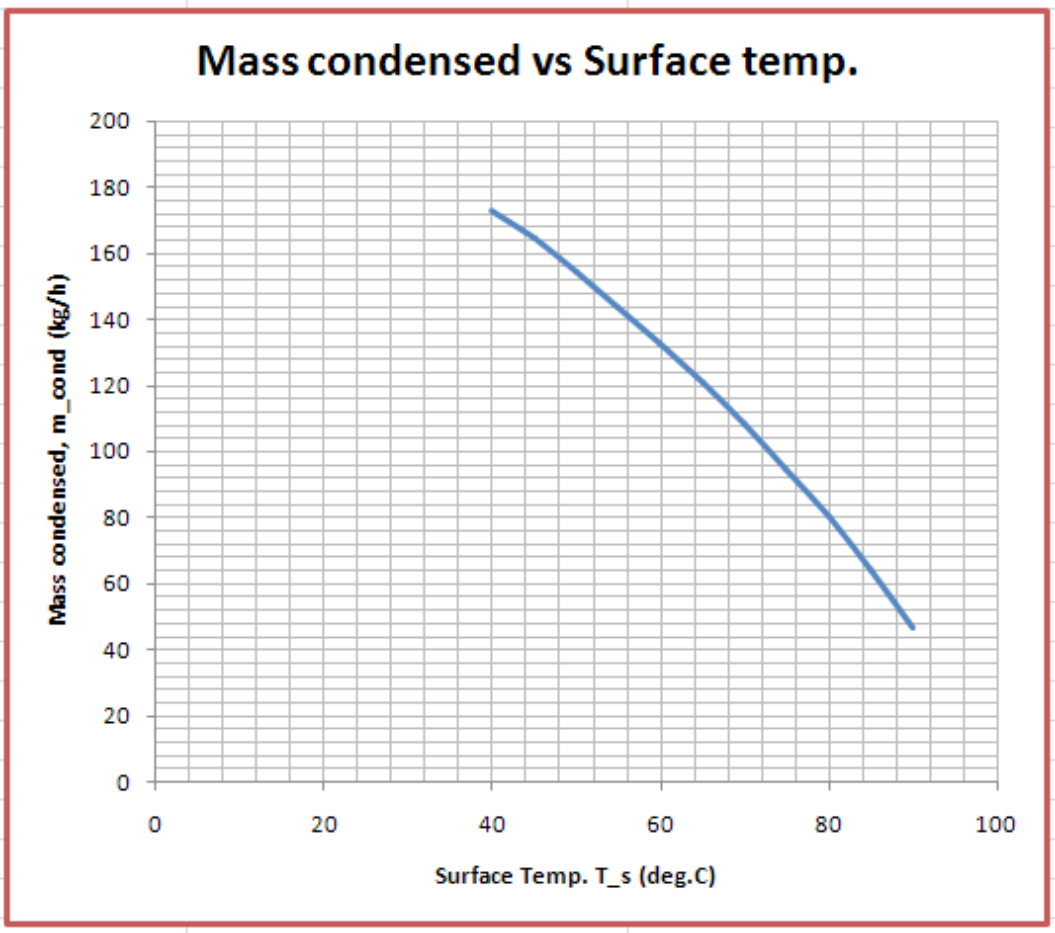
T_s_lower= 40 C

T_s_higher= 90

Change these two values between 0 and 90 and click CommandButton2

| T_s (deg.C) | h_avg (W.m^2.C) | Q (W) | m_cond_per_hour (kg/h) |
|---|---|---|---|
| 40 | 6470.780 | 116474.047 | 172.700 |
| 45 | 6673.633 | 110114.948 | 164.231 |
| 50 | 6852.391 | 102785.871 | 154.206 |
| 55 | 7052.117 | 95203.579 | 143.680 |
| 60 | 7279.946 | 87359.347 | 132.632 |
| 65 | 7534.148 | 79108.556 | 120.830 |
| 70 | 7815.814 | 70342.327 | 108.094 |
| 75 | 8148.413 | 61113.096 | 94.486 |
| 80 | 8553.905 | 51323.430 | 79.839 |
| 85 | 9081.401 | 40866.307 | 63.966 |
| 90 | 9840.315 | 29520.944 | 46.497 |

5. Now, plot m_cond against T_s:

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6. Now, we can easily change the range of T_s as we desire, by changing cells C334 and C335. **As an example, for T_s between the limits 10 and 60 C:** Change cells C344 and C335 as shown and click CommandButton2 and we get:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 331 | | | | | |
| 332 | | To plot h_avg, Q and m_cond against T_s: | | | |
| 333 | | | | | CommandButton2 |
| 334 | | T_s_lower= | 10 | C | |
| 335 | | T_s_higher= | 60 | | |
| 336 | | Change these two values between 0 and 90 and click CommandButton2 | | | |
| 337 | | | | | |
| 338 | | T_s (deg.C) | h_avg (W.m^2.C) | Q (W) | m_cond_per_hour (kg/h) |
| 339 | | 10 | 5470.928 | 147715.068 | 211.608 |
| 340 | | 15 | 5616.357 | 143217.103 | 206.328 |
| 341 | | 20 | 5770.951 | 138502.813 | 200.674 |
| 342 | | 25 | 5932.619 | 133483.928 | 194.512 |
| 343 | | 30 | 6093.910 | 127972.119 | 187.557 |
| 344 | | 35 | 6271.017 | 122284.830 | 180.263 |
| 345 | | 40 | 6470.780 | 116474.047 | 172.700 |
| 346 | | 45 | 6673.633 | 110114.948 | 164.231 |
| 347 | | 50 | 6852.391 | 102785.871 | 154.206 |
| 348 | | 55 | 7052.117 | 95203.579 | 143.680 |
| 349 | | 60 | 7279.946 | 87359.347 | 132.632 |

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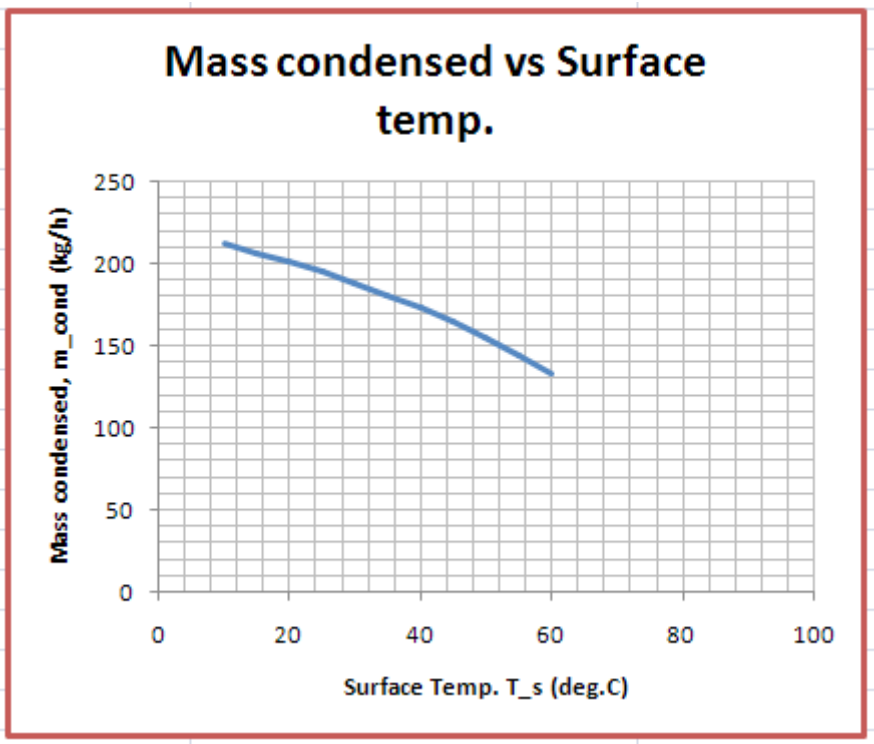
And, the plot up-dates itself immediately:




==========

**Prob.3.2.25.** Consider a vertical tube, 1 m high, 80 mm dia, maintained at a uniform temp of 50 C, exposed to sat. steam at atm. pressure. Find out the heat transfer and steam condensation rate.

Note: This is the same as Prob.3.2.5, which was solved with Mathcad.

Now, we shall solve it with EXCEL.

**EXCEL Solution:**

This is the case of condensation of steam on a vertical cylinder.

Equations for the case of a vertical cylinder are the same as those for a vertical plate, if the Dia of the cylinder is much larger than the thickness of condensate film, which is generally true. Only change is in calculation of Q where the surface area for cylinder is: $\pi$ . D . L:

**First, let us write a VBA Function for the cases of: condensation of steam on a Vertical Cylinder:**

---

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```
Function Condensation_VCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Vertical Cylinder  held at T_s

'This is the same as for vertical plates, when the cyl dia is large...
'relative to the thickness of the liquid film (which is generally true)

'Calculates h_avg for laminar, wavy and turbulent film condensation
'based on value of Re_f

'Results are returned as an Array

'Note: positive x direction is from top of plate downwards; y dirn is from left to right
'x is the distance from top, b is the breadth of plate perpendicular to paper

Dim g As Double, Re As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, delta_l As Double, Re_f As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

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```
'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling"
delta_l = ((4 * k_l * mu_l * (T_sat - T_s) * L) / _
(rho_l * (rho_l - rho_v) * g * h_fg_prime)) ^ (1 / 4) '[m]....thickness of film at a
'distance L from top

Re = (4 * g * rho_l * (rho_l - rho_v) * delta_l ^ 3) / (3 * mu_l ^ 2) '...film Reynolds No.

If (Re > 0) And (Re <= 30) Then  'laminar film

   h_avg = 1.47 * k_l * Re ^ (-1 / 3) * (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = Re 'Film Reynolds No. for laminar flow

ElseIf (Re > 30) And (Re <= 1800) Then 'wavy - laminar flow in film

      h_avg = ((Re * k_l) / (1.08 * Re ^ 1.22 - 5.2)) * (g / nu_l ^ 2) ^ (1 / 3)

      Re_f = (4.81 + (3.7 * L * k_l * (T_sat - T_s) / (mu_l * h_fg_prime)) * (g / nu_l ^ 2) ^ (1 / 3)) ^ 0.82

ElseIf (Re > 1800) Then    'turb. flow in film

   h_avg = ((Re * k_l) / (8750 + 58 * Pr_l ^ (-0.5) * (Re ^ 0.75 - 253))) * _
   (g / nu_l ^ 2) ^ (1 / 3)

   Re_f = ((0.069 * L * k_l * Pr_l ^ 0.5 * (T_sat - T_s) / (mu_l * h_fg_prime)) * _
   (g / nu_l ^ 2) ^ (1 / 3) - 151 * Pr_l ^ 0.5 + 253) ^ (4 / 3)

End If
```

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```
Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s

Condensation_VCyl_Steam = Application.Transpose(Array(delta_l, Re_f, h_avg, Q, m_condensed))

End Function
```

---

**Now, let us solve the above problem.**

Remember that the Function returns an Array containing: delta_L, Re_f, h_avg, Q and m_cond as earlier.

1. Set up the EXCEL worksheet, enter data:

| | A | B | C | D |
|---|---|---|---|---|
| 381 | | | | |
| 382 | | Data: | | |
| 383 | | T_sat | 100.000 | C |
| 384 | | T_s | 50.000 | C |
| 385 | | D | 0.080 | m |
| 386 | | L | 1.000 | m |
| 387 | | | | |
| 388 | | delta_L | | m |
| 389 | | Re_f | | |
| 390 | | h_avg | | W/m^2.C |
| 391 | | Q | | W |
| 392 | | m_cond | | kg/s |
| 393 | | m_cond_per_hour | | kg/h |

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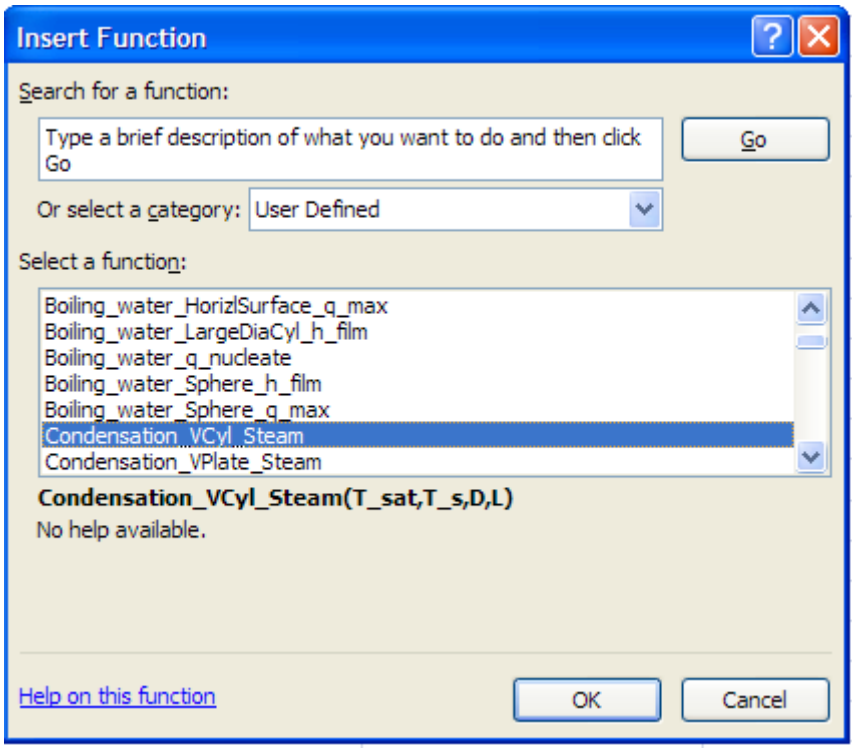
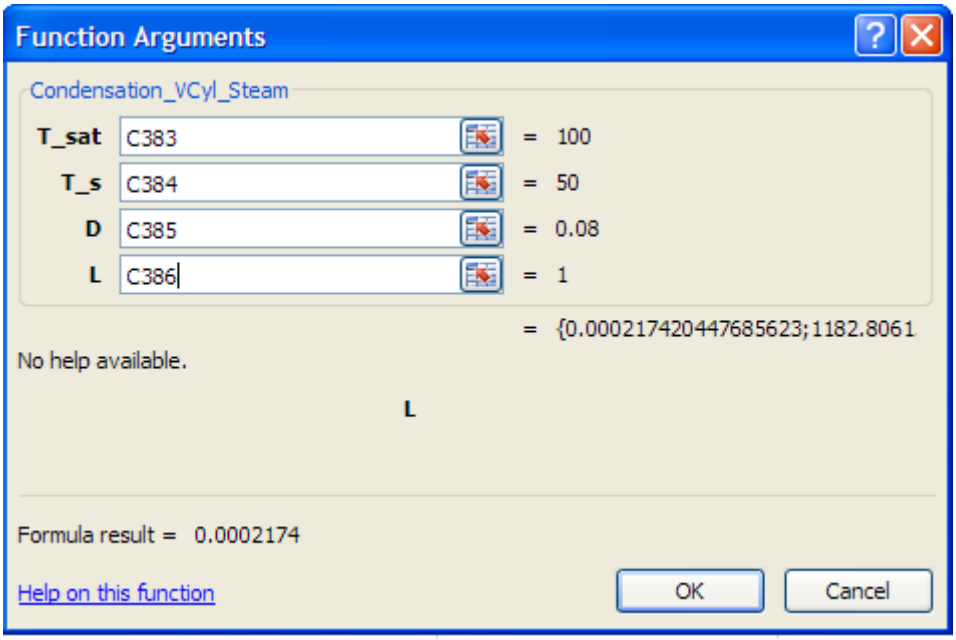
2. Now, **select the 5 consecutive cells** (i.e. cells C388 to C392) and enter the array Function for condensation of steam on Vertical cylinder: (See the previous problem for procedure of inserting a 'built-in' Function):




Click OK. Fill up the screen that shows up as follows:

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**Now, IMPORTANT**: Press (Ctrl + Shift + Return or OK), since it is an Array Function. We get the results as shown below:

C389 {=Condensation_VCyl_Steam(C383,C384,C385,C386)}

| | A | B | C | D |
|---|---|---|---|---|
| 381 | | | | |
| 382 | | Data: | | |
| 383 | | T_sat | 100.000 | C |
| 384 | | T_s | 50.000 | C |
| 385 | | D | 0.080 | m |
| 386 | | L | 1.000 | m |
| 387 | | | | |
| 388 | | delta_L | 0.0002174 | m |
| 389 | | Re_f | 1182.806 | |
| 390 | | h_avg | 5604.515 | W/m^2.C |
| 391 | | Q | 70428.408 | W |
| 392 | | m_cond | 0.029350 | kg/s |
| 393 | | m_cond_per_hour | | kg/h |

In the above, the Function entered can be seen in the Formula bar.

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Complete the last step by calculating m_cond per hour by multiplying the value in cell C392 by 3600. We get:

C393 =C392*3600

| | A | B | C | D |
|---|---|---|---|---|
| 381 | | | | |
| 382 | | Data: | | |
| 383 | | T_sat | 100.000 | C |
| 384 | | T_s | 50.000 | C |
| 385 | | D | 0.080 | m |
| 386 | | L | 1.000 | m |
| 387 | | | | |
| 388 | | delta_L | 0.0002174 | m |
| 389 | | Re_f | 1182.806 | |
| 390 | | h_avg | 5604.515 | W/m^2.C |
| 391 | | Q | 70428.408 | W |
| 392 | | m_cond | 0.029350 | kg/s |
| 393 | | m_cond_per_hour | 105.661 | kg/h |

**Thus:**

**The condensation rate is: 105.661 kg/h … Ans.**

***Note: This matches with the results obtained in Prob. 3.2.5.***

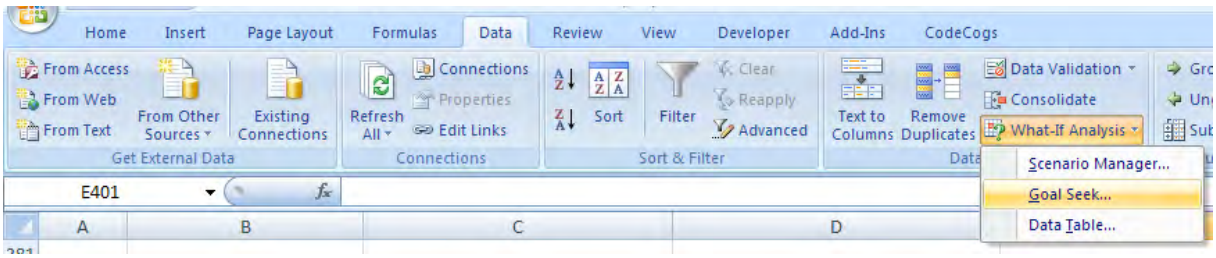
---

**(b) What should be the value of T_s to get a condensation rate of 125 kg/h?**

This is calculated by applying Goal Seek on cell C393 to make it 125 by changing cell C384 (i.e.value of T_s):

Following are the steps:

Go to Data – WhatIf Analysis – Goal Seek:

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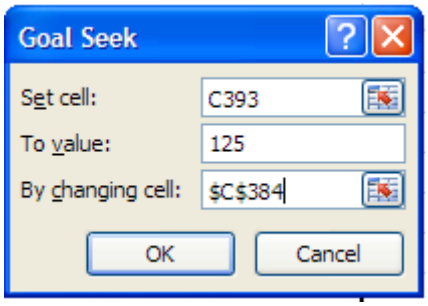
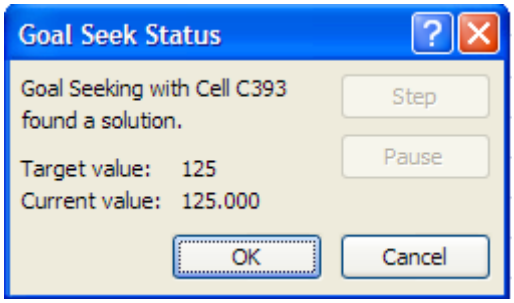
Click on Goal Seek. Fill up the screen that pops up as shown:




Click OK:




i.e. Goal Seek has found a solution. Click OK and see the value in cell C384 to get the required T_s:

C384 | 33.5260406613353

| | A | B | C | D |
|---|---|---|---|---|
| 381 | | | | |
| 382 | | Data: | | |
| 383 | | T_sat | 100.000 | C |
| 384 | | T_s | 33.526 | C |
| 385 | | D | 0.080 | m |
| 386 | | L | 1.000 | m |
| 387 | | | | |
| 388 | | delta_L | 0.0002380 | m |
| 389 | | Re_f | 1242.837 | |
| 390 | | h_avg | 5084.249 | W/m^2.C |
| 391 | | Q | 84941.168 | W |
| 392 | | m_cond | 0.034722 | kg/s |
| 393 | | m_cond_per_hour | 125.000 | kg/h |

**i.e. Value of T_s required to get a condensation rate of 125 kg/h is: 33.53 C … Ans.**

**Note:** Values of delta_L, Re_f, h_avg, and Q also have got up-dated immediately.

==========

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**Prob.3.2.26.** Consider a horizontal tube, 1 m long, 50 mm dia, maintained at a uniform temp of 34 C, exposed to sat. steam at 0.2 bar. pressure. Find out the heat transfer and steam condensation rate.

**EXCEL Solution:**

Note that at 0.2 bar, sat. temp. T_sat = 60.06 C

Let us write a VBA Function to calculate h, Q and m_condensed for condensation of steam on a Horizl cylinder:

```
Function Condensation_on_HCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of Steam at T_sat on a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

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```
'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L

Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HCyl_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Read the comments in the above program to know what each line does.

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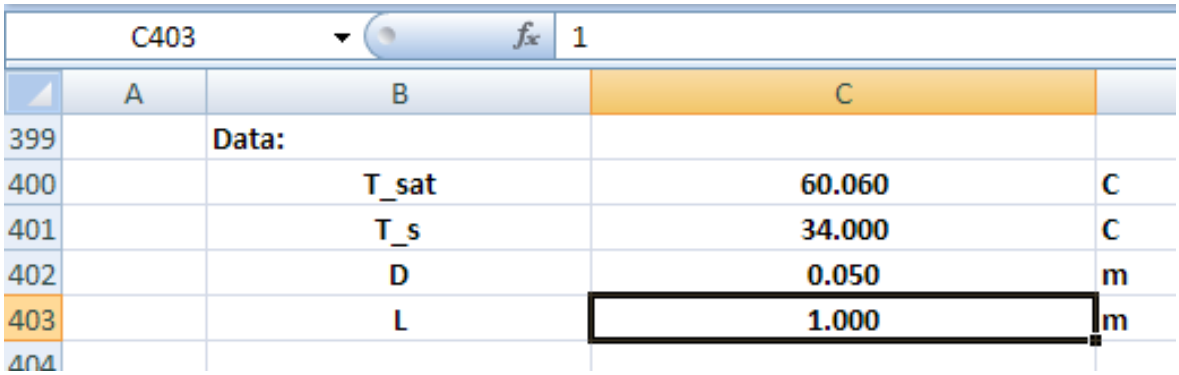
Now, let us use this program to solve the above problem:

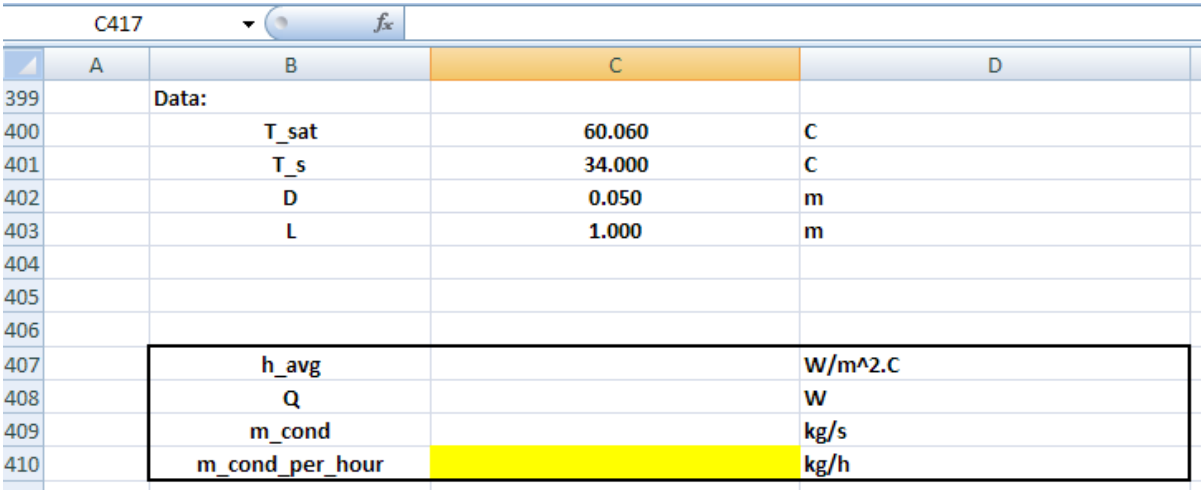
Following are the steps:

1. Set up the EXCEL worksheet, enter data:



| | A | B | C | |
|---|---|---|---|---|
| 399 | | Data: | | |
| 400 | | T_sat | 60.060 | C |
| 401 | | T_s | 34.000 | C |
| 402 | | D | 0.050 | m |
| 403 | | L | 1.000 | m |
| 404 | | | | |

2. Set up the worksheet for further calculation, remembering that we are going to use an Array Function:



| | A | B | C | D |
|---|---|---|---|---|
| 399 | | Data: | | |
| 400 | | T_sat | 60.060 | C |
| 401 | | T_s | 34.000 | C |
| 402 | | D | 0.050 | m |
| 403 | | L | 1.000 | m |
| 404 | | | | |
| 405 | | | | |
| 406 | | | | |
| 407 | | h_avg | | W/m^2.C |
| 408 | | Q | | W |
| 409 | | m_cond | | kg/s |
| 410 | | m_cond_per_hour | | kg/h |

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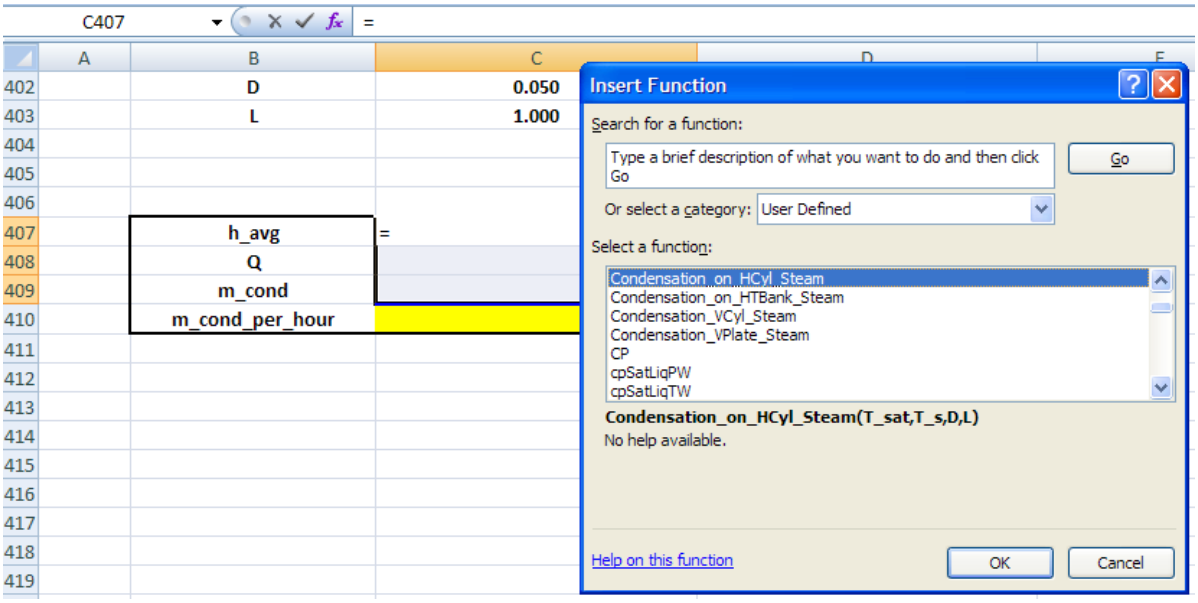
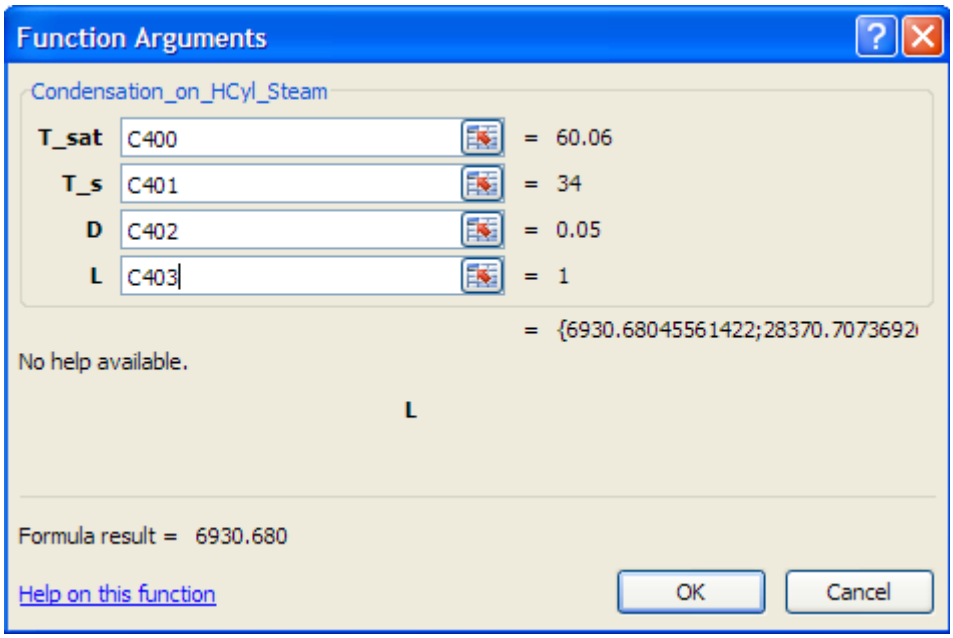
3. Now, select three consecutive cells in column C, i.e. cells C407, C408 and C409, and insert the array Function:




4. Press OK. We get the following screen; fill it up as shown:

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5. **IMPORTANT:** Now, apply (Ctrl + Shift + Return), since it is an Array Function. We get:

C407 fx {=Condensation_on_HCyl_Steam(C400,C401,C402,C403)}

| | A | B | C | D |
|---|---|---|---|---|
| 399 | | Data: | | |
| 400 | | T_sat | 60.060 | C |
| 401 | | T_s | 34.000 | C |
| 402 | | D | 0.050 | m |
| 403 | | L | 1.000 | m |
| 404 | | | | |
| 405 | | | | |
| 406 | | | | |
| 407 | | h_avg | 6930.680 | W/m^2.C |
| 408 | | Q | 28370.707 | W |
| 409 | | m_cond | 0.011664 | kg/s |
| 410 | | m_cond_per_hour | | kg/h |

In the Formula bar, see the Array Function used for Condensation on Horizl cylinder.

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6. Complete the last step to get condensation rate in kg/h in cell C410, by multiplying value in cell C409 by 3600:

D417

| | A | B | C | D |
|---|---|---|---|---|
| 399 | | Data: | | |
| 400 | | T_sat | 60.060 | C |
| 401 | | T_s | 34.000 | C |
| 402 | | D | 0.050 | m |
| 403 | | L | 1.000 | m |
| 404 | | | | |
| 405 | | | | |
| 406 | | | | |
| 407 | | h_avg | 6930.680 | W/m^2.C |
| 408 | | Q | 28370.707 | W |
| 409 | | m_cond | 0.011664 | kg/s |
| 410 | | m_cond_per_hour | 41.990 | kg/h |

**Thus:**

**Heat transfer, q = 28370.7 W … ans.**

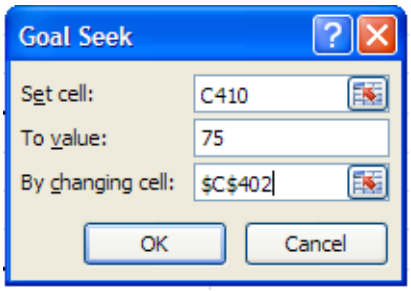
**Condensation rate = 41.99 kg/h …. Ans.**

---

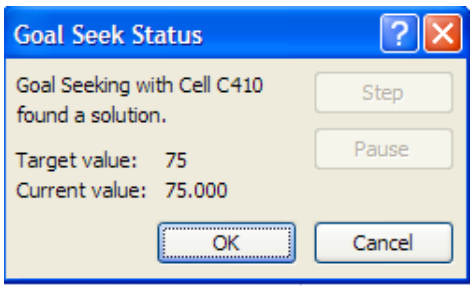
**(b) What diameter is required to get a condensation rate of 75 kg/h?**

Use Goal Seek in EXCEL to make cell C410 to 75 by changing cell C402 (i.e. value of D):

Click on: Data – WhatIf Analysis_GoalSeek. We get the following screen; fill it up as shown:




Click OK:

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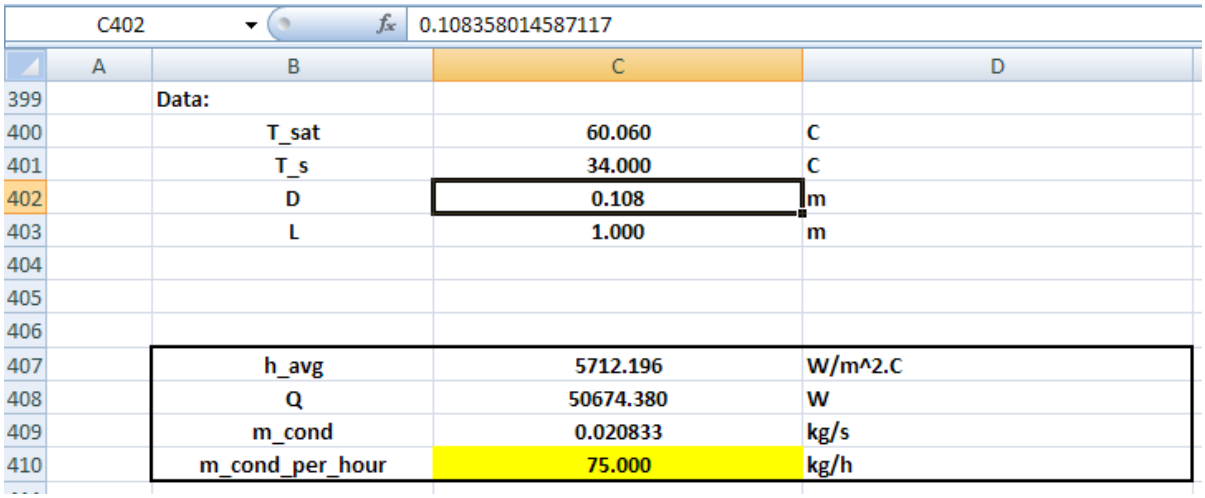
Goal seek has found a solution. Again, click OK and see the new value of D in cell C402:



C402 | 0.108358014587117

| | A | B | C | D |
|---|---|---|---|---|
| 399 | | Data: | | |
| 400 | | T_sat | 60.060 | C |
| 401 | | T_s | 34.000 | C |
| 402 | | D | 0.108 | m |
| 403 | | L | 1.000 | m |
| 404 | | | | |
| 405 | | | | |
| 406 | | | | |
| 407 | | h_avg | 5712.196 | W/m^2.C |
| 408 | | Q | 50674.380 | W |
| 409 | | m_cond | 0.020833 | kg/s |
| 410 | | m_cond_per_hour | 75.000 | kg/h |

**Thus:**

**Dia required to get 75 kg/h of condensation rate is: D = 0.108 m … Ans.**

==========

**Practically, the case of condensation on a bank of horizontal tubes in a vertical tier is more important than condensation on a single tube.**

**This is particularly relevant to Steam condensers where there are many columns (or Tiers), each Tier having many horizontal tubes, on which steam will condense at the condenser pressure.**

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**Let us write a VBA Function for the case of condensation of steam on a Tier of horizontal tubes:**

```
Function Condensation_on_HTBank_Steam(T_sat As Double, T_s As Double, D As Double, L As Double, _
N As Double, N_total As Double) As Variant

'Condensation of Steam at T_sat on a Horizl Tube Bank held at T_s
'i.e. A vertical Tier of N horizl tubes

'Input: T_sat, T_s (C), D, L (m), N (no. of tubes per Tier), N_total (total no. of
'tubes in all Tiers)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


'Properties of liquid at Tf:

rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
mu_l = SatH2O_muf_T(T_f + 273.15)
cp_l = SatH2O_cpf_T(T_f + 273.15)
k_l = SatH2O_kf_T(T_f + 273.15)
nu_l = mu_l / rho_l
Pr_l = SatH2O_Prf_T(T_f + 273.15)


'Properties of vapour and h_fg at Tsat:

rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
h_fg = SatH2O_hfg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * N * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L


Q = h_avg * N_total * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HTBank_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

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Now, use this Function to solve the following problem:

**Problem 3.2.27**. Consider a one-pass Condenser which has a total of 64 tubes, arranged in a square array. Tubes are 1.25 m long, 12 mm OD. Water flowing inside the tubes maintains the wall temp at 25 C. If the steam is condensing on the outside of tubes at 0.1 bar pressure, find: (i) the heat transfer (ii) the condensation rate.

**EXCEL Solution:**

We have, at 0.1 bar: T_sat = 45.81 C, and, T_s = 25 C.

Since it is a square array, there are 8 Tiers, each Tier having 8 horizontal tubes. i.e. N = 8, N_total = 64

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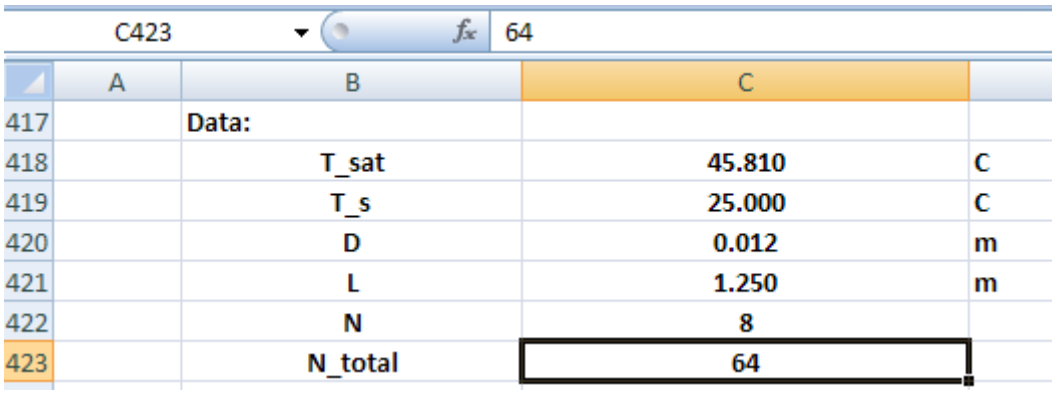
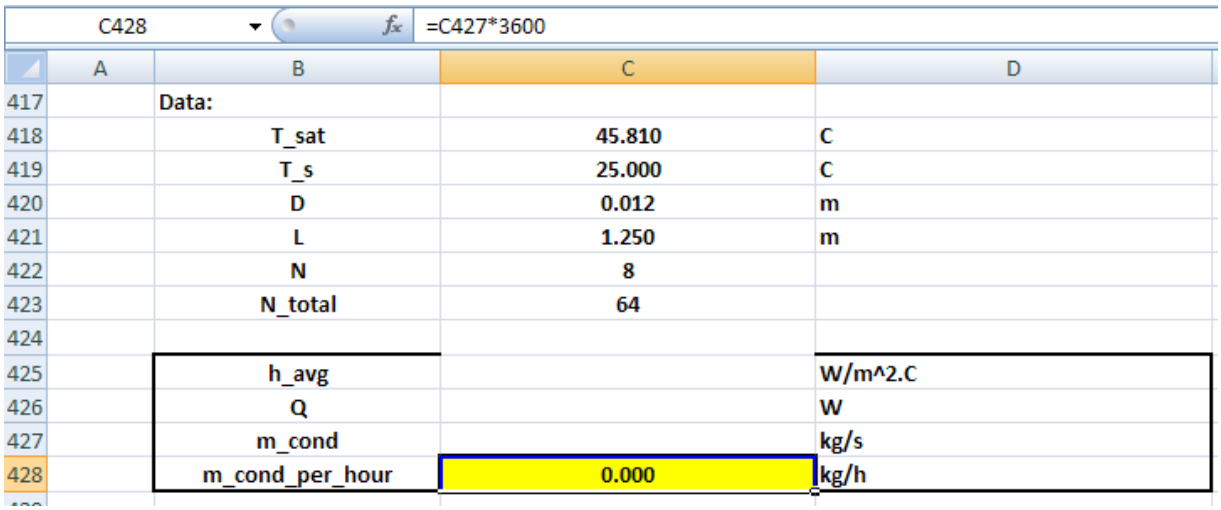
1. Set up the EXCEL worksheet, enter data:



C423 | fx | 64

| | A | B | C | |
|---|---|---|---|---|
| 417 | | Data: | | |
| 418 | | T_sat | 45.810 | C |
| 419 | | T_s | 25.000 | C |
| 420 | | D | 0.012 | m |
| 421 | | L | 1.250 | m |
| 422 | | N | 8 | |
| 423 | | N_total | 64 | |

2. Set up the calculations for the Tube Bank, using the Array Function just written:



C428 | fx | =C427*3600

| | A | B | C | D |
|---|---|---|---|---|
| 417 | | Data: | | |
| 418 | | T_sat | 45.810 | C |
| 419 | | T_s | 25.000 | C |
| 420 | | D | 0.012 | m |
| 421 | | L | 1.250 | m |
| 422 | | N | 8 | |
| 423 | | N_total | 64 | |
| 424 | | | | |
| 425 | | h_avg | | W/m^2.C |
| 426 | | Q | | W |
| 427 | | m_cond | | kg/s |
| 428 | | m_cond_per_hour | 0.000 | kg/h |

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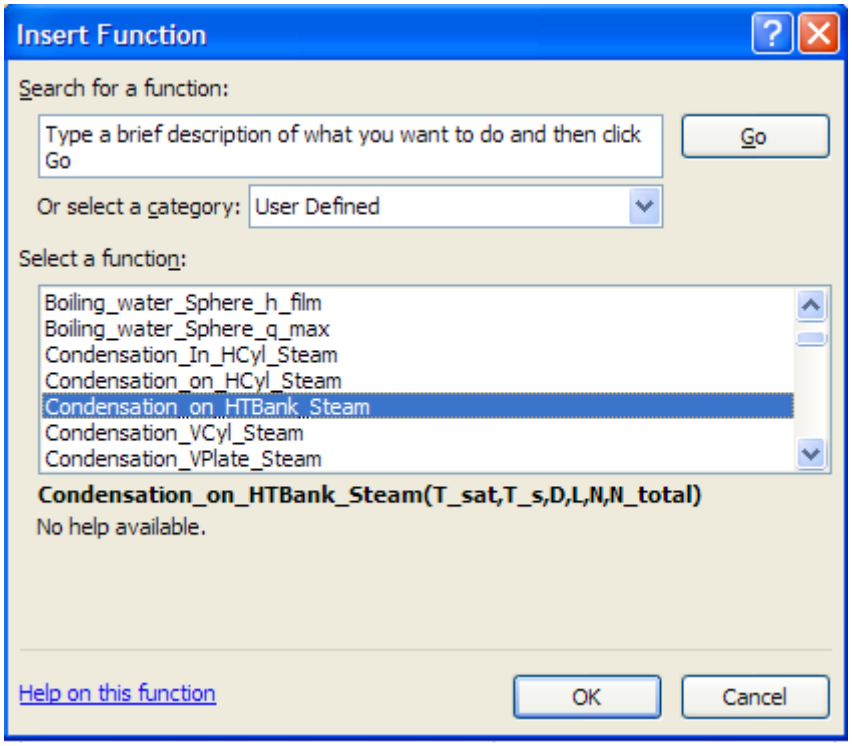
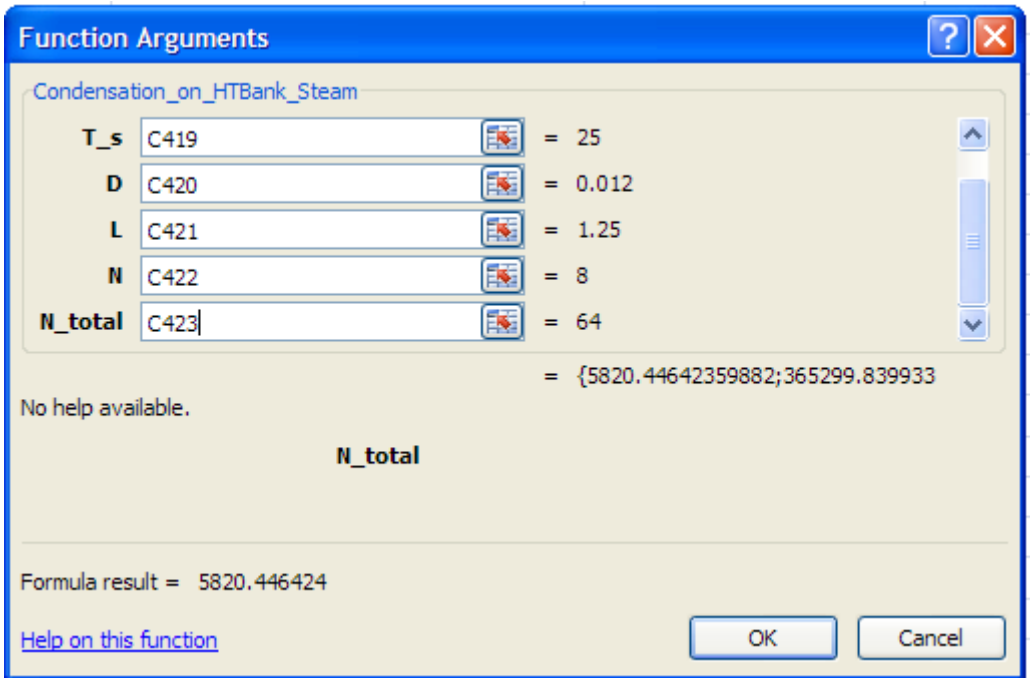
3. Select the cells C425, C426 and C427 and enter the Array Function:




Click OK. We get the following screen; fill it up as shown:

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**IMPORTANT:** Now, press (Ctrl + Shift + Enter), since it is an Array Function. We get:

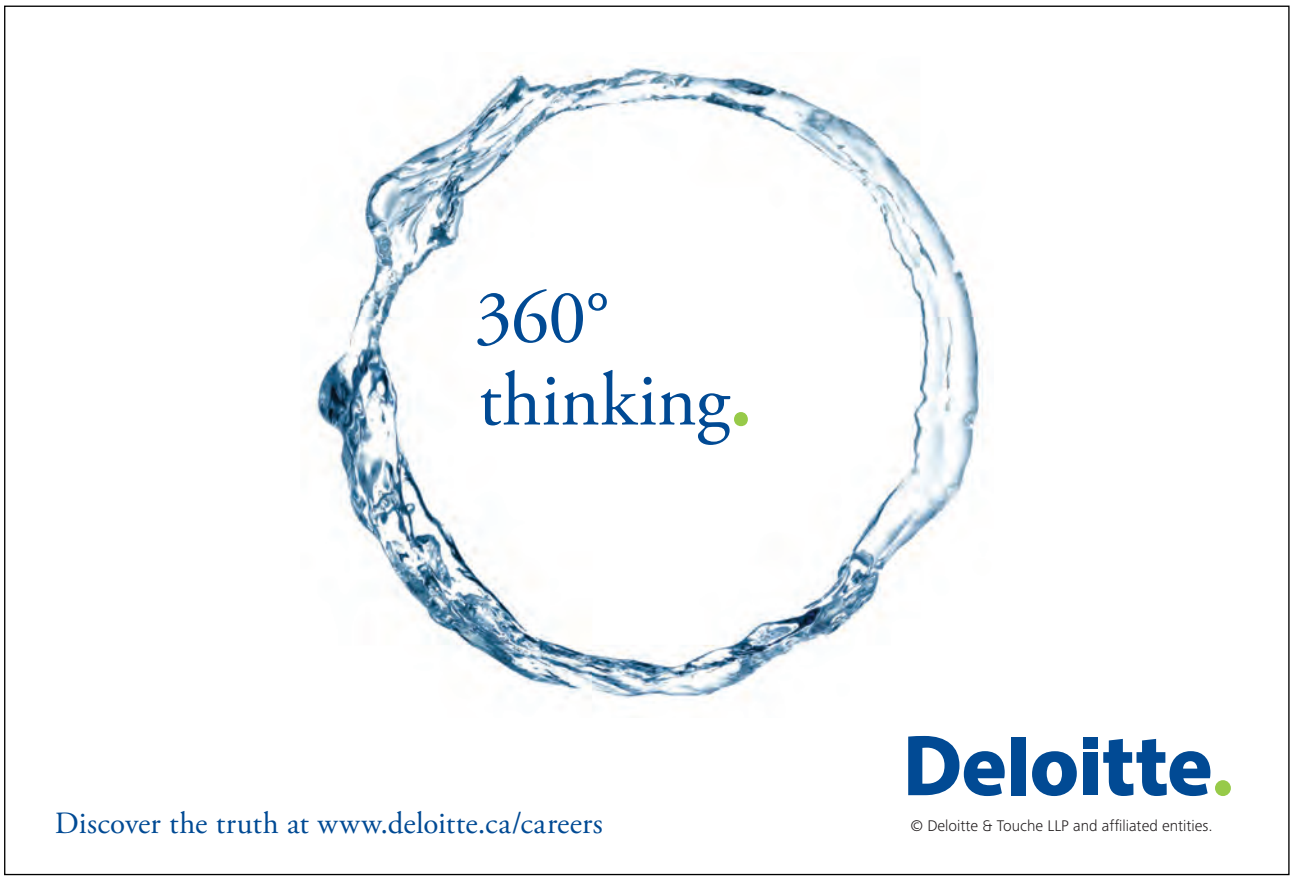
C427 | {=Condensation_on_HTBank_Steam(C418,C419,C420,C421,C422,C423)}

| | A | B | C | D |
|---|---|---|---|---|
| 417 | | Data: | | |
| 418 | | T_sat | 45.810 | C |
| 419 | | T_s | 25.000 | C |
| 420 | | D | 0.012 | m |
| 421 | | L | 1.250 | m |
| 422 | | N | 8 | |
| 423 | | N_total | 64 | |
| 424 | | | | |
| 425 | | h_avg | 5820.446424 | W/m^2.C |
| 426 | | Q | 365299.839933 | W |
| 427 | | m_cond | 0.149004 | kg/s |
| 428 | | m_cond_per_hour | 536.413 | kg/h |

**Thus:**

**Heat transferred, Q = 365299.84 W …. Ans.**

**Condensation rate = 536.413 kg/h … Ans.**

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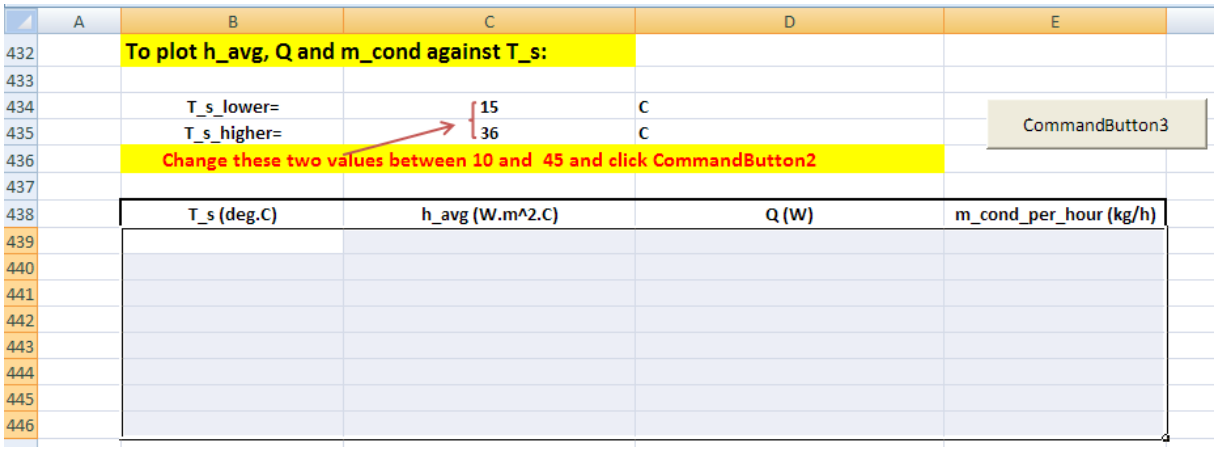
**(b) For T_s varying from 15 C to 36 C, plot the condensation rate against T_s:**

Let us write a VBA program to do this.

1. Before that, set up a Table as shown:

We plan to give lower limit and upper limit of T_s, and then the program should fill up the Table for 7 equally divided values of T_s and also the program should be executed with a ControlButton.

For the procedure of inserting an ActiveX ControlButton, see Problem 3.2.22.




2. Now, double click on the ControlButton3 and we see the VBA program behind it:

---

Private Sub CommandButton3_Click()

End Sub

---

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3. Now, modify this program as follows to perform the desired calculation steps:

```
Private Sub CommandButton3_Click()


Dim i As Integer
Dim T_s_initial As Double, T_s_final As Double, Inc As Double

T_s_initial = Range("C434") 'starting value for T_s
T_s_final = Range("C435") 'starting value for T_s

Inc = (T_s_final - T_s_initial) / 7

For i = 0 To 7

Range("C419") = T_s_initial + i * Inc 'Sets the T_s value to the starting or initial value

'Immediately, all other values will up-date themselves.
'And, copy them to their respective places in the Table:

Cells(439 + i, 2) = Range("C419") 'copies value of T_s to Table
Cells(439 + i, 3) = Range("C425") 'copies value of h_avg to Table
Cells(439 + i, 4) = Range("C426") 'copies value of Q to Table
Cells(439 + i, 5) = Range("C428") 'copies value of m_cond_per_hour to Table

Next i

End Sub
```

Read the comments in the above code to know what each line does.

4. Now, click on the CommandButton3 and immediately the calculations are done and the Table is filled up:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 432 | | To plot h_avg, Q and m_cond against T_s: | | | |
| 433 | | | | | |
| 434 | | T_s_lower= | 15 | C | CommandButton3 |
| 435 | | T_s_higher= | 36 | C | |
| 436 | | You may change T_s such that: T_s higher < 45 and T_s_lower > 0, Then click CommandButton3. | | | |
| 437 | | | | | |
| 438 | | T_s (deg.C) | h_avg (W.m^2.C) | Q (W) | m_cond_per_hour (kg/h) |
| 439 | | 15 | 5115.017 | 475291.304 | 689.929 |
| 440 | | 18 | 5298.407 | 444393.233 | 647.304 |
| 441 | | 21 | 5501.440 | 411646.348 | 601.680 |
| 442 | | 24 | 5734.516 | 377201.641 | 553.249 |
| 443 | | 27 | 6007.410 | 340798.132 | 501.597 |
| 444 | | 30 | 6327.369 | 301700.556 | 445.604 |
| 445 | | 33 | 6723.455 | 259754.282 | 384.996 |
| 446 | | 36 | 7247.254 | 214419.168 | 318.922 |

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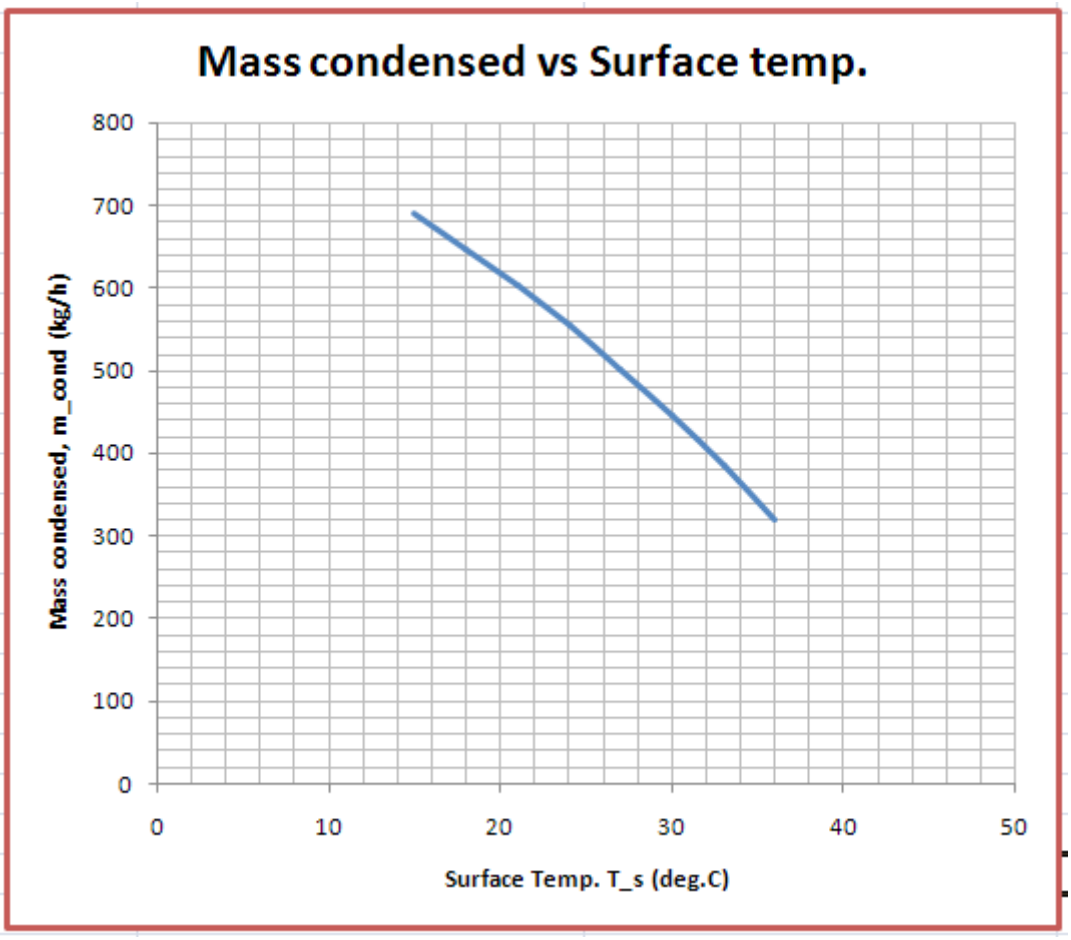
5. Now, plot m_cond against T_s:




6. Now, we can easily change the range of T_s as we desire, by changing cells C434 and C435. **As an example, for T_s between the limits 10 and 40 C:** Change cells C434 and C435 as shown and click CommandButton3 and we get:

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 432 | | To plot h_avg, Q and m_cond against T_s: | | | |
| 433 | | | | | |
| 434 | | T_s_lower= | 10 | C | CommandButton3 |
| 435 | | T_s_higher= | 40 | C | |
| 436 | | You may change T_s such that: T_s higher < 45 and T_s_lower > 0, Then click CommandButton3. | | | |
| 437 | | | | | |

| 438 | T_s (deg.C) | h_avg (W.m^2.C) | Q (W) | m_cond_per_hour (kg/h) |
|---|---|---|---|---|
| 439 | 10 | 4850.412 | 523846.512 | 756.077 |
| 440 | 14.28571429 | 5074.320 | 482441.042 | 699.735 |
| 441 | 18.57142857 | 5335.103 | 438276.570 | 638.814 |
| 442 | 22.85714286 | 5641.651 | 390538.681 | 572.053 |
| 443 | 27.14285714 | 6021.628 | 339010.287 | 499.048 |
| 444 | 31.42857143 | 6503.887 | 282095.465 | 417.343 |
| 445 | 35.71428571 | 7189.665 | 218910.618 | 325.493 |
| 446 | 40 | 8349.039 | 146296.424 | 218.624 |

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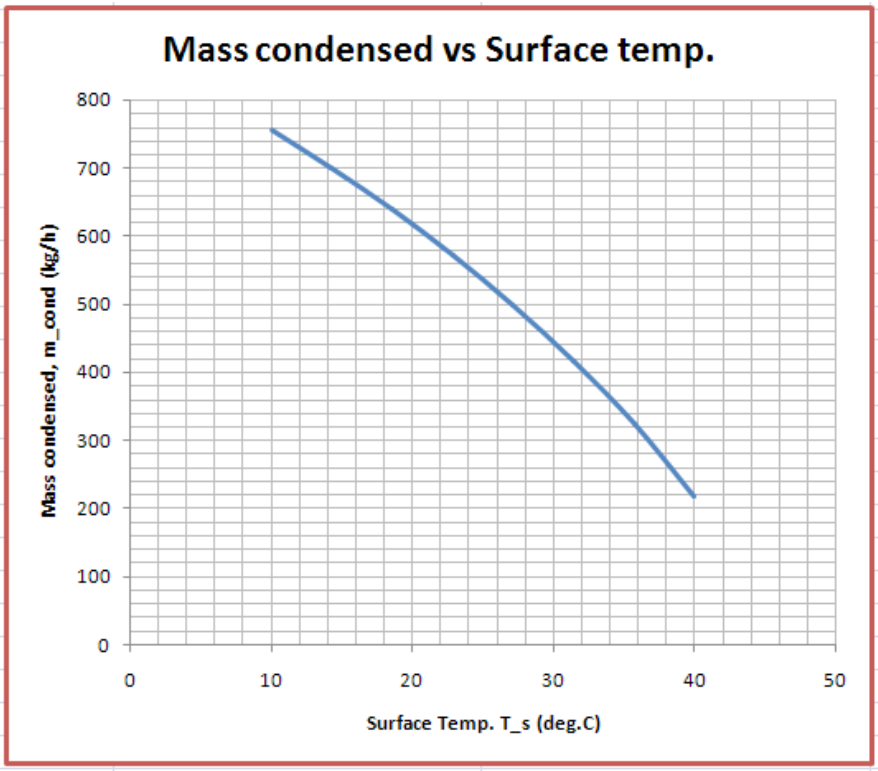
And, the plot updates itself immediately:

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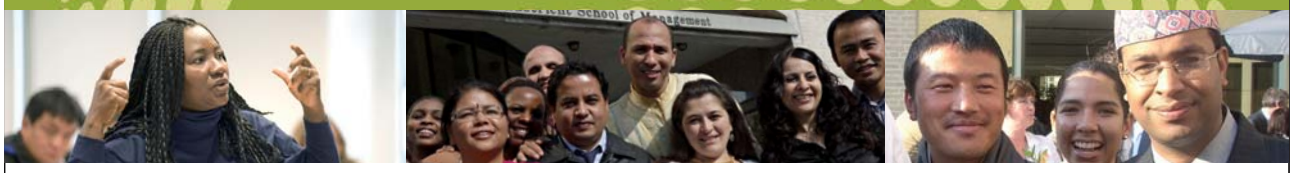

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**Prob.3.2.28.** Consider a horizontal tube, 4 m long, 30 mm ID, maintained at a uniform temp of 110 C, inside which sat. steam at 2.701 bar condenses. Assuming low vap. velocity, find out the heat transfer and steam condensation rate.

**EXCEL Solution:**

Note that at 2.701 bar, sat. temp. T_sat = 130 C

Let us write a VBA Function to calculate h, Q and m_condensed for condensation of steam on inside a Horizontal cylinder:

---

```
Function Condensation_In_HCyl_Steam(T_sat As Double, T_s As Double, D As Double, L As Double, U_v As Double) As Variant

'Condensation of Steam at T_sat inside a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m), U_v (vap. velocity, m/s)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double, mu_v As Double, Re_vap As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = 1 / SatH2O_vf_T(T_f + 273.15)
 mu_l = SatH2O_muf_T(T_f + 273.15)
 cp_l = SatH2O_cpf_T(T_f + 273.15)
 k_l = SatH2O_kf_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = SatH2O_Prf_T(T_f + 273.15)


 'Properties of vapour and h_fg at Tsat:

 rho_v = 1 / SatH2O_vg_T(T_sat + 273.15)
 mu_v = SatH2O_mug_T(T_sat + 273.15)
 h_fg = SatH2O_hfg_T(T_sat + 273.15)
```

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```
'Calculations:

h_fg_prime = h_fg + (3 / 8) * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

Re_vap = rho_v * U_v * D / mu_v '..Vapour Reynolds No...must be < 35000!!

If (Re_vap <= 35000) Then

h_avg = 0.555 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg internal heat tr coeff over L

ElseIf (Re_vap > 35000) Then

    MsgBox ("Re_vap must be <= 35000. Now, Re_vap =" & Re_vap)

End If


Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_In_HCyl_Steam = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, let us solve the above problem:

1. Set up the EXCEL worksheet, enter data:

| | A | B | C | D |
|---|---|---|---|---|
| 475 | | | | |
| 476 | | **Data:** | | |
| 477 | | **T_sat** | **130.000** | **C** |
| 478 | | **T_s** | **110.000** | **C** |
| 479 | | **D** | **0.030** | **m** |
| 480 | | **L** | **4.000** | **m** |
| 481 | | **U_v** | **0** | **m/s...vap. Velocity** |
| 482 | | | | |

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2. Set up the calculations for the condensation inside the horizl cylinder, using the Array Function just written:

C487 =C486*3600

| | A | B | C | D |
|---|---|---|---|---|
| 475 | | | | |
| 476 | | Data: | | |
| 477 | | T_sat | 130.000 | C |
| 478 | | T_s | 110.000 | C |
| 479 | | D | 0.030 | m |
| 480 | | L | 4.000 | m |
| 481 | | U_v | 0 | m/s...vap. Velocity |
| 482 | | | | |
| 483 | | | | |
| 484 | | h_avg | | W/m^2.C |
| 485 | | Q | | W |
| 486 | | m_cond | | kg/s |
| 487 | | m_cond_per_hour | 0.000 | kg/h |

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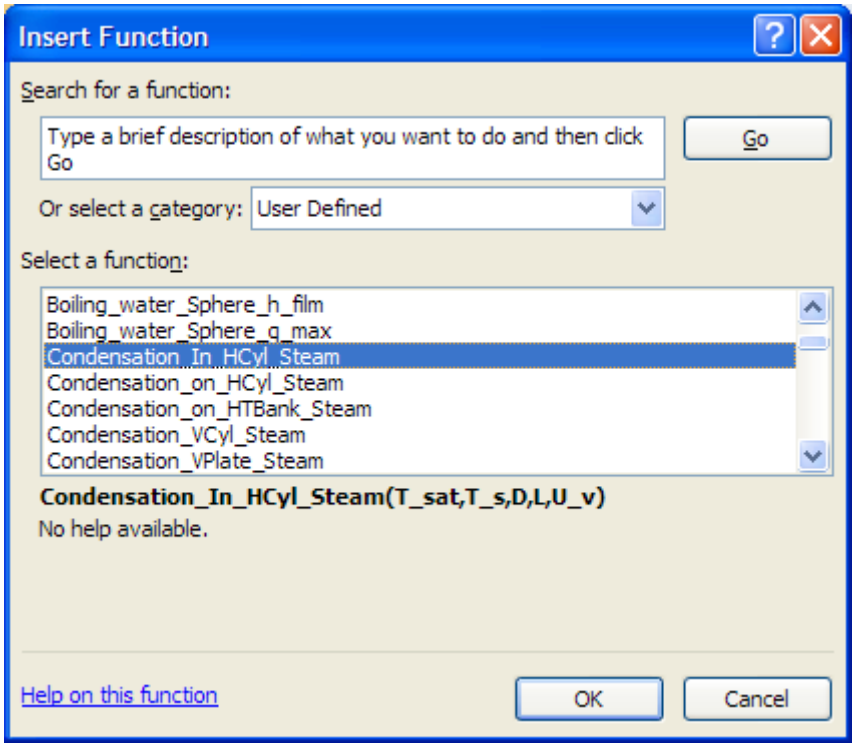
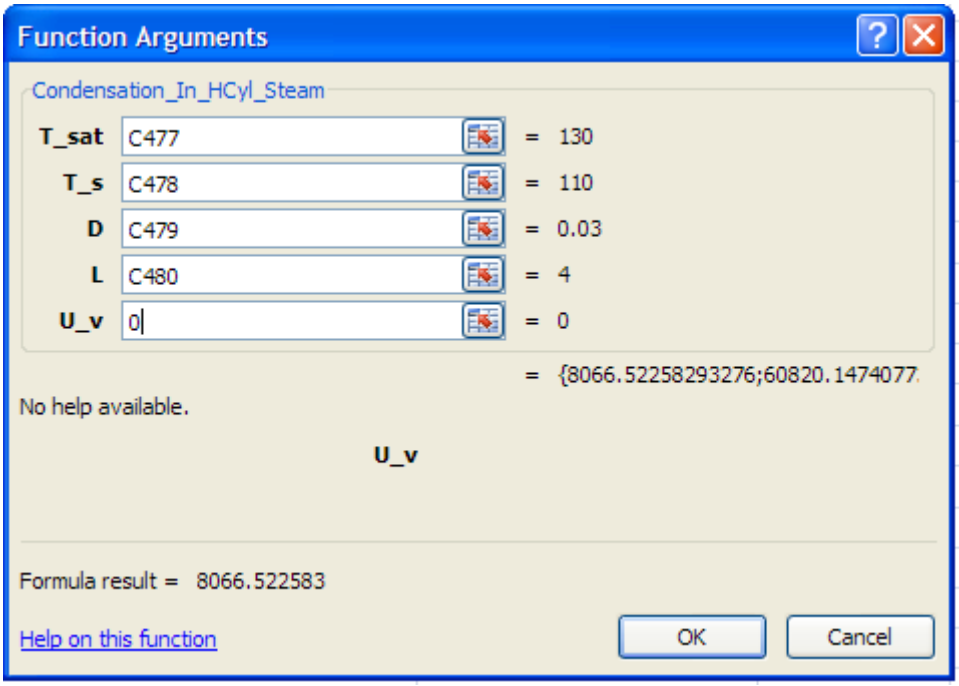
3. Select the cells C484, C485 and C486 and enter the Array Function:




Click OK. We get the following screen; fill it up as shown:

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**IMPORTANT:** Now, press (Ctrl + Shift + Enter), since it is an Array Function. We get:

C484 | {=Condensation_In_HCyl_Steam(C477,C478,C479,C480,C481)}

| | A | B | C | D |
|---|---|---|---|---|
| 476 | | Data: | | |
| 477 | | T_sat | 130.000 | C |
| 478 | | T_s | 110.000 | C |
| 479 | | D | 0.030 | m |
| 480 | | L | 4.000 | m |
| 481 | | U_v | 0 | m/s...vap. Velocity |
| 482 | | | | |
| 483 | | | | |
| 484 | | h_avg | 8066.522583 | W/m^2.C |
| 485 | | Q | 60820.147408 | W |
| 486 | | m_cond | 0.027578 | kg/s |
| 487 | | m_cond_per_hour | 99.281 | kg/h |

**Thus:**

**Heat transferred, Q = 60820.15 W …. Ans.**

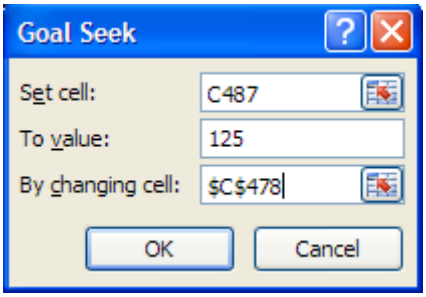
**Condensation rate = 99.28 kg/h … Ans.**

---

**(b) What should be the surface temp, T_s, if we need to get a condensation rate of 125 kg/h?**

Use Goal Seek in EXCEL to make cell C487 to 125 by changing cell C478 (i.e. value of T_s):

Click on: Data – WhatIf Analysis_GoalSeek. We get the following screen; fill it up as shown:

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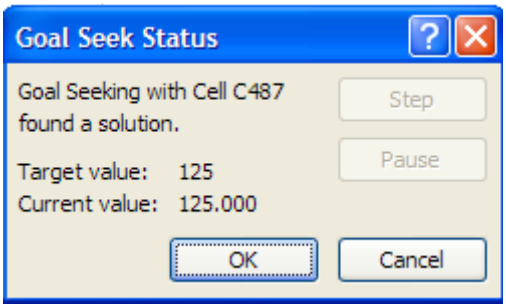
Click OK:



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Goal seek has found a solution. Again, click OK and see the new value of T_s in cell C478:

C478 fx 102.362061326824

| | A | B | C | D |
|---|---|---|---|---|
| 476 | | Data: | | |
| 477 | | T_sat | 130.000 | C |
| 478 | | T_s | 102.362 | C |
| 479 | | D | 0.030 | m |
| 480 | | L | 4.000 | m |
| 481 | | U_v | 0 | m/s...vap. Velocity |
| 482 | | | | |
| 483 | | | | |
| 484 | | h_avg | 7389.803180 | W/m^2.C |
| 485 | | Q | 76996.261555 | W |
| 486 | | m_cond | 0.034722 | kg/s |
| 487 | | m_cond_per_hour | 125.000 | kg/h |

**Thus:**

**Surface temp required to get 125 kg/h of condensation rate is: T_s = 102.36 C … Ans.**

==========

**VBA Functions for properties of Ammonia (NH3) (i.e. R717):**

Many times, we need properties of NH3 at a given temp while solving problems on condensation. *But, EXCEL does not have built-in property functions for NH3.*

So, we shall use these Tables on properties of Sat. NH3, shown below and write Functions in VBA to find out various properties. The required properties are found at the given temp (in K) by interpolation.

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Following are the steps:

1. First, enter the data table in EXCEL as shown below:

Ref: https://www.thermalfluidscentral.org/encyclopedia/index.php/Thermophysical_Properties:_Ammonia

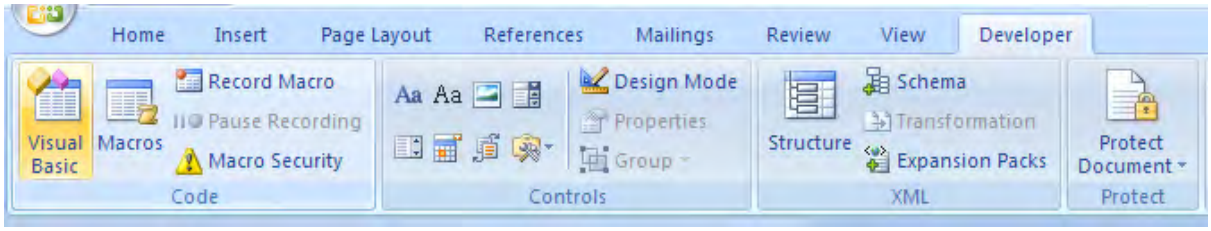
**Thermophysical Properties: Ammonia**

Ammonia, $NH_3$, Molecular Mass: 17.0, ($T_{sat}$ = 239.9 K; Tm = 195.5 K)

| Temp. K | $p_v$ saturation pressure ($10^5$ Pa) | $h_{lv}$ latent heat (kJ/kg) | $\rho_\ell$ liquid density (kg/m³) | $\rho_v$ vapor density (kg/m³) | $\mu_\ell$ liquid viscosity (10-6 N-s/m²) | $\mu_v$ vapor viscosity ($10^{-6}$ N-s/m²) | $k_\ell$ liquid thermal conductivity (W/m-K) | $k_v$ vapor thermal conductivity (W/m-K) | σ liquid surface tension a ($10^{-3}$N/m) | $c_{p,\ell}$ liquid specific heat (kJ/kg-K) | $c_{p,v}$ vapor specific heat a (kJ/kg-K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 200 | 0.008646 | 1477 | 728.9 | 0.08899 | 407 | 7.64 | 0.709 | 0 | 0 | 4.606 | 1.979 |
| 210 | 0.017746 | 1451 | 717.5 | 0.1746 | 369 | 8.02 | 0.685 | 0 | 0 | 4.375 | 2.033 |
| 220 | 0.033811 | 1425 | 705.8 | 0.319 | 334 | 8.4 | 0.661 | 0.0158 | 0 | 4.346 | 2.083 |
| 230 | 0.060439 | 1398 | 693.7 | 0.5489 | 302 | 8.78 | 0.638 | 0.0171 | 0 | 4.382 | 2.151 |
| 240 | 0.10226 | 1369 | 681.4 | 0.8972 | 273 | 9.16 | 0.615 | 0.0184 | 33.9 | 4.431 | 2.237 |
| 250 | 0.16496 | 1339 | 668.9 | 1.404 | 245 | 9.54 | 0.592 | 0.0199 | 31.5 | 4.483 | 2.343 |
| 260 | 0.25529 | 1307 | 656.1 | 2.115 | 220 | 9.93 | 0.569 | 0.0211 | 29.2 | 4.539 | 2.467 |
| 270 | 0.381 | 1273 | 642.9 | 3.086 | 197 | 10.31 | 0.546 | 0.0224 | 26.9 | 4.597 | 2.611 |
| 280 | 0.55077 | 1237 | 629.2 | 4.38 | 176 | 10.7 | 0.523 | 0.0239 | 24.7 | 4.662 | 2.776 |
| 290 | 0.77413 | 1198 | 615 | 6.071 | 157.7 | 11.07 | 0.5 | 0.0256 | 22.4 | 4.734 | 2.963 |
| 300 | 1.0614 | 1159 | 600.2 | 8.247 | 141 | 11.45 | 0.477 | 0.0277 | 20.2 | 4.815 | 3.18 |
| 310 | 1.4235 | 1113 | 584.6 | 11.01 | 126 | 11.86 | 0.454 | 0.0302 | 18 | 4.909 | 3.428 |
| 320 | 1.8721 | 1066 | 568.2 | 14.51 | 113.4 | 12.29 | 0.431 | 0.0332 | 15.9 | 5.024 | 3.725 |
| 330 | 2.4196 | 1014 | 550.9 | 18.89 | 101.9 | 12.74 | 0.408 | 0.0368 | 13.7 | 5.17 | 4.088 |
| 340 | 3.0789 | 958 | 532.4 | 24.4 | 92.1 | 13.22 | 0.385 | 0.0415 | 11.7 | 5.366 | 4.545 |
| 350 | 3.8641 | 895 | 512.3 | 31.34 | 83.2 | 13.74 | 0.361 | 0.0467 | 9.6 | 5.639 | 5.144 |
| 360 | 4.7902 | 825 | 490.3 | 40.18 | 75.4 | 14.35 | 0.337 | 0.0536 | 7.67 | 6.042 | 5.978 |
| 370 | 5.874 | 745 | 465.5 | 51.65 | 68.5 | 15.07 | 0.313 | 0.0614 | 5.74 | 6.677 | 7.217 |
| 380 | 7.1352 | 649 | 436.5 | 67.16 | 61.1 | 15.96 | 0.286 | 0.07 | 3.98 | 7.795 | 9.312 |
| 390 | 8.5977 | 529 | 400.2 | 89.85 | 50.3 | 17.14 | 0.254 | 0.08 | 2.21 | 10.27 | 13.86 |

Note that temp range is: T = 200 K – 390 K.

2. Now, the various properties are required as a function of T. So, the VBA program we write will search for the temp in the column B and if it finds the exact match, it will return the required property by reading the same in that row. If the exact temp match is not available (this is the more likely scenario), it will locate two consecutive cells where one temp is lower than required T, and the other temp is higher than T. Also, the corresponding values of the property at these two temperatures are noted. Then, a linear interpolation is made between these two values of the property and the same is returned.
3. Now, write the VBA code. Go to Developer – Visual Basic –

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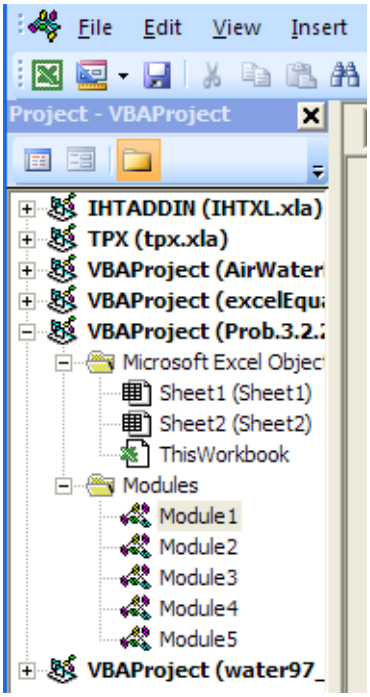
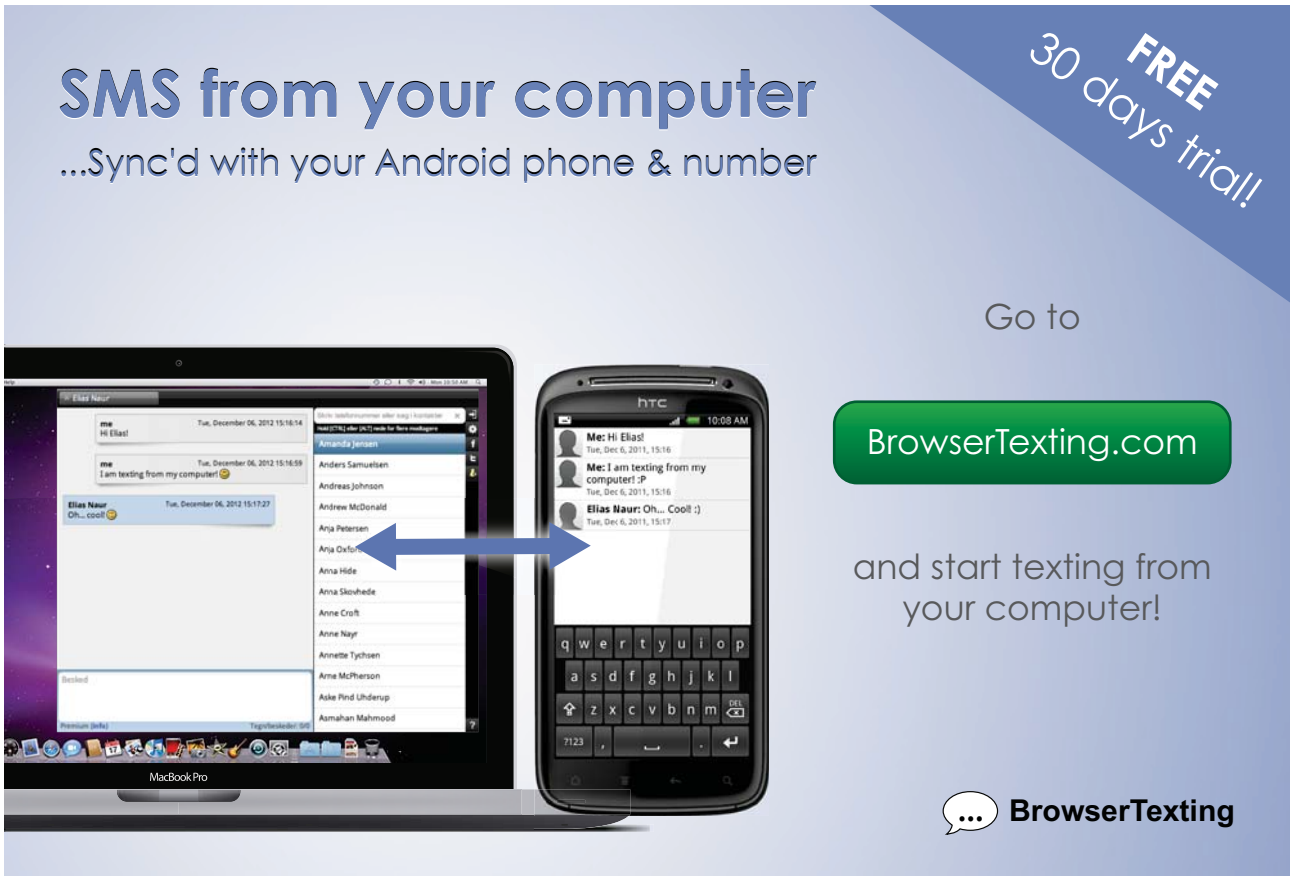
Click on Visual Basic:




And, click on Module1, wherein VBA programs for properties of Air were written. Go to the end of that Module and write programs for NH3.

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One example is shown below, for density of liquid, rho_f:

```
(General)                                    (Declarations)
Function SatNH3_rho_f_T(T As Double) As Double
'gives density of liq rho_f(kg/m^3)as a function of T (K) at sat. temp T(K)
'Reads rho_f values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rho_f1 As Double, rho_f2 As Double

If T < 200 Or T > 390 Then

 MsgBox ("T must be between 200 K and 390 K !!")
 End
 End If

For i = 0 To 19

   If Cells(96 + i, 13) = T Then
      SatNH3_rho_f_T = Cells(96 + i, 16)
   End If
   If Cells(96 + i, 13) < T And Cells(96 + i + 1, 13) > T Then
      T_1 = Cells(96 + i, 13).Value
      T_2 = Cells(96 + i + 1, 13).Value
      rho_f1 = Cells(96 + i, 16).Value
      rho_f2 = Cells(96 + i + 1, 16).Value
      SatNH3_rho_f_T = (rho_f1 + (T - T_1) * (rho_f2 - rho_f1) / (T_2 - T_1))
   End If

Next i

End Function
```

In the above code:

1st line: declares name of the function, with dimensions of variables involved

Lines 2, 3: comments – explain about the Function

Line 4, 5: declarations of dimensions of internal variables, i.e. variables available only inside the Function

Line 6 to 9: If statement to give an error message if value of T entered is beyond the values available in the Table

Line 10: Beginning of For…Next construct. Note that the construct will search in the 20 lines of the Table

Lines 11, 12, 13: If the exact match for T is found, Function returns the value of 'rho' in the column P

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Lines 14 to 20: If he exact match of T is not there in the Table, then locate the values of T just below T and just above T,, and name them as T_1 and T_2. Also, note the corresponding values of rho as rho_f1 and rho_f2. And, then, calculate the value of rho at the required T by interpolation.

Line 21: Go to the next i in the loop

Line 22: End statement of Function.

4. Similar Functions are written for other properties of NH3, as functions of T. i.e.

For density of vap….SatNH3__rho_g_T(T)

For th. conductivity of liq….SatNH3_k_f_T(T)

For th. conductivity of vap….SatNH3_k_g_T(T)

For sp. heat of liq….SatNH3_cp_f_T(T)

For sp. heat of vap….SatNH3_cp_g_T(T)

For surface tension….SatNH3_sigma_f_T(T)

For dynamic viscosity of liq….SatNh3_mu_f_T(T)

For dynamic viscosity of vap….SatNh3_mu_g_T(T), and

For heat of vaporization of liq….SatNh3_h_fg_T(T)

---

Now, using these VBA Functions for properties of NH3, write Functions for condensation of Sat NH3 on vertical plates, vertical cylinders, Horizl cylinder, Tube bank with horizl tubes in a vertical tier, condensation inside horizontal cylinder etc.

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One example of a VBA program for **condensation of NH3 on the outside of a horizl cylinder** is shown below:

```
Function Condensation_on_HCyl_NH3(T_sat As Double, T_s As Double, D As Double, L As Double) As Variant

'Condensation of NH3 at T_sat on a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = SatNH3_rho_f_T(T_f + 273.15)
 mu_l = SatNH3_mu_f_T(T_f + 273.15)
 cp_l = SatNH3_cp_f_T(T_f + 273.15)
 k_l = SatNH3_k_f_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = cp_l * mu_l / k_l


 'Properties of vapour and h_fg at Tsat:

 rho_v = SatNH3_rho_g_T(T_sat + 273.15)
 h_fg = SatNH3_h_fg_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + 0.68 * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

h_avg = 0.729 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg heat tr coeff over L

Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s


Condensation_on_HCyl_NH3 = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

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Now, the above program is an Array Function and returns h_avg, Q and Mass_condensed in a vertical array.

**Let us solve a problem using this Function:**

**Prob. 3.2.29.** Sat. NH3 vapour at 10 C condenses on the outside of a 2 cm OD, 5 m long horizontal tube whose outer surface is maintained at -10 C. Determine: (a) rate of heat transfer (b) rate of condensation of NH3.

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**EXCEL Solution:**

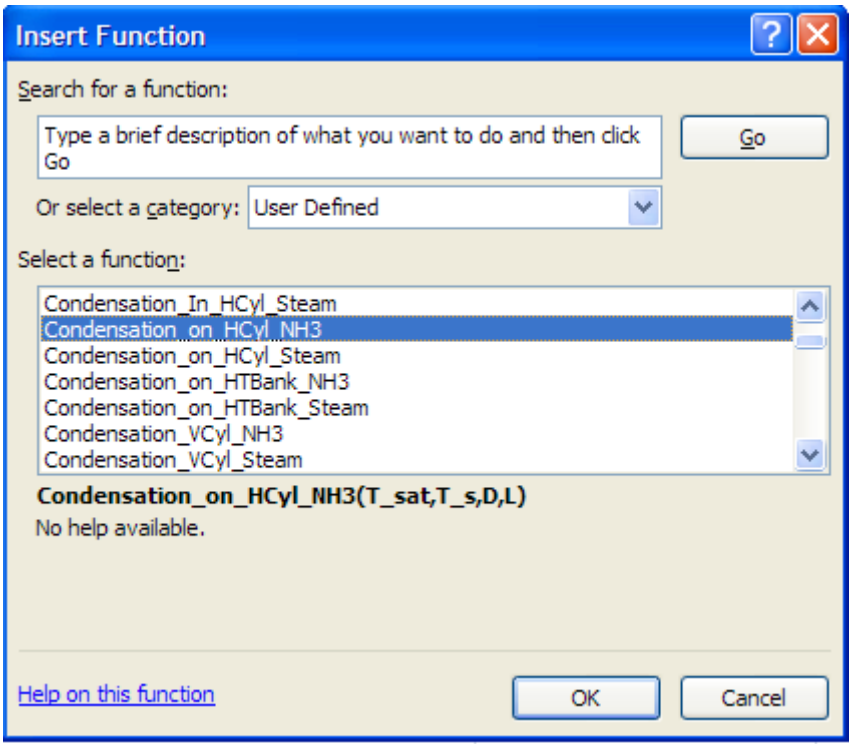
We shall use the VBA program written above for condensation on a horizl tube:

Following are the steps:

1. Set up the EXCEL worksheet, enter data:

| | A | B | C | D |
|---|---|---|---|---|
| 493 | | | | |
| 494 | | Data: Fluid: Ammonia | | |
| 495 | | T_sat | 10.000 | C |
| 496 | | T_s | -10.000 | C |
| 497 | | D | 0.020 | m |
| 498 | | L | 5.000 | m |
| 499 | | | | |
| 500 | | | | |
| 501 | | | | |
| 502 | | h_avg | | W/m^2.C |
| 503 | | Q | | W |
| 504 | | m_cond | | kg/s |
| 505 | | m_cond_per_hour | 0.000 | kg/h |

2. Select cells C502to C504 and enter the Array Function for condensation of NH3 on the outside of a horizontal cylinder. Remember to press (Ctrl + Shift + Enter) after selecting the Function from the 'User Defined' category, and entering the required parameters for the Function:

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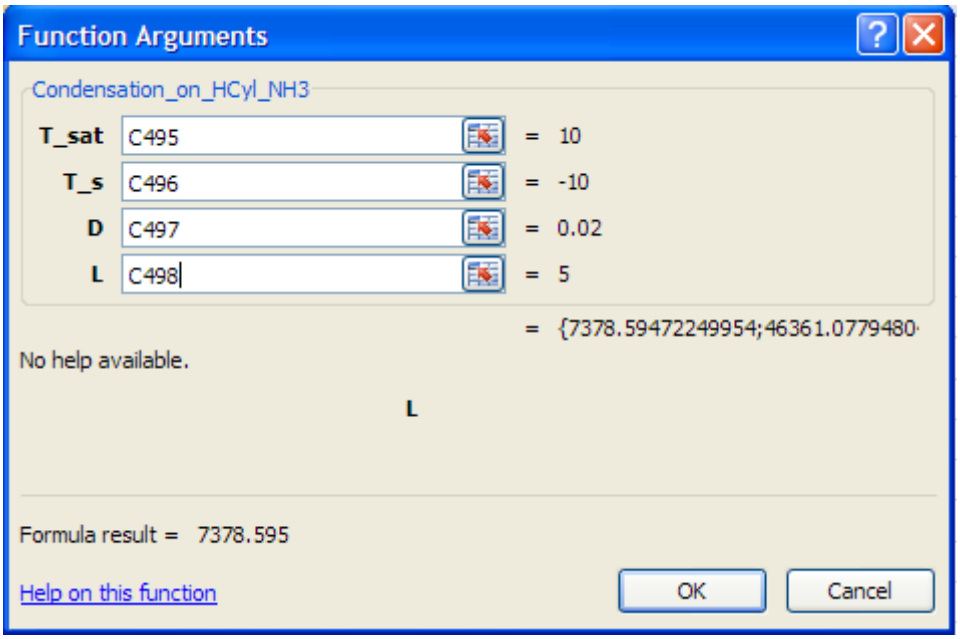


Press (Ctrl+Shift+OK) since it is an Array Function, and we get:

C502 {=Condensation_on_HCyl_NH3(C495,C496,C497,C498)}

| | A | B | C | D |
|---|---|---|---|---|
| 493 | | | | |
| 494 | | Data: Fluid: Ammonia | | |
| 495 | | T_sat | 10.000 | C |
| 496 | | T_s | -10.000 | C |
| 497 | | D | 0.020 | m |
| 498 | | L | 5.000 | m |
| 499 | | | | |
| 500 | | | | |
| 501 | | | | |
| 502 | | h_avg | 7378.595 | W/m^2.C |
| 503 | | Q | 46361.078 | W |
| 504 | | m_cond | 0.036008 | kg/s |
| 505 | | m_cond_per_hour | 129.630 | kg/h |
| 506 | | | | |

**Thus:**

**h_avg = 7378.6 W/m^2.C …. Ans.**

**Q = 46361.1 W …. Ans.**

**m_cond_per_hour = 129.63 kg/h …. Ans.**

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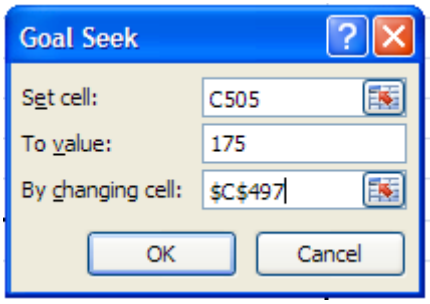
**(b) What should be the diameter if we need to have a condensation rate of 175 kg/h?**

This is easily calculated by applying Goal seek to cell C505 (i.e. m_cond_per_hour) to make it 175 by changing cell C497 (i.e. D).

The procedure is:

Go to Data – WhatIf Analysis – Goal Seek Click on Goal Seek. We get the following screen; fill it up as shown:



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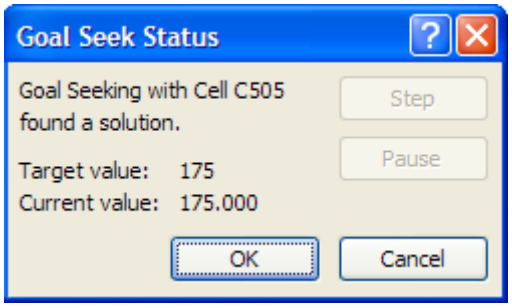
Click OK. We get:




Goal Seek has found a solution. Again, click OK and see the result in cell C497:

C497 | 0.0298406322119435

| | A | B | C | D |
|---|---|---|---|---|
| 493 | | | | |
| 494 | | Data: Fluid: Ammonia | | |
| 495 | | T_sat | 10.000 | C |
| 496 | | T_s | -10.000 | C |
| 497 | | D | 0.0298 | m |
| 498 | | L | 5.000 | m |
| 499 | | | | |
| 500 | | | | |
| 501 | | | | |
| 502 | | h_avg | 6676.197 | W/m^2.C |
| 503 | | Q | 62587.419 | W |
| 504 | | m_cond | 0.048611 | kg/s |
| 505 | | m_cond_per_hour | 175.000 | kg/h |

**Thus: Value of D required to get a condensation rate of 175 kg/h = 0.0298 m … Ans.**

**Note that correspondingly, values of h_avg and Q also have changed.**

==========

**VBA Functions for properties of Refrigerant R134a:**

R134a is a substitute for R12, since R12 is phased out due to its contribution to ozone layer depletion. *But, EXCEL does not have built-in property functions for R134a.*

So, we shall use these Tables on properties of Sat. R134a, shown below and write Functions in VBA to find out various properties. The required properties are found at the given temp (in K) by interpolation.

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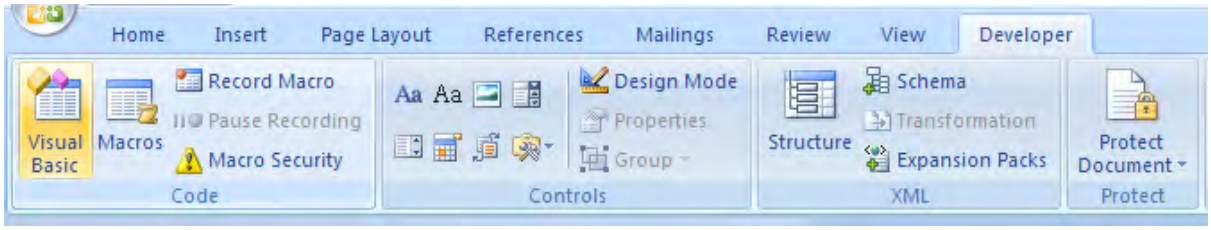
Following are the steps:

1. First, enter the data table in EXCEL as shown below:

| | M | N | O | P | Q | R | S | T | U | V | W | X |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 117 | Ref: https://www.thermalfluidscentral.org/encyclopedia/index.php/Thermophysical_Properties:_Freon%C2%AE-134a | | | | | | | | | | | |
| 118 | **Thermophysical Properties: Freon®-134a** | | | | | | | | | | | |
| 119 | | | | | | | | | | | | |
| 120 | Freon-134a, CF3CH2F, Molecular Mass: 102.0, ($T_{sat}$ = -26.4°C; $T_m$ = -101 °C) | | | | | | | | | | | |
| 121 | TTemp. K | $p_v$ saturation pressure ($10^5$ Pa) | $h_{lv}$ latent heat (kJ/kg) | $\rho_\ell$ liquid density ($10^3$ kg/m³) | $\rho_v$ vapor density (kg/m³) | $\mu_\ell$ liquid viscosity ($10^{-3}$ N-s/m²) | $\mu_v$ vapor viscosity ($10^{-7}$ N-s/m²) | $k_\ell$ liquid thermal conductivity (W/m-K) | $k_v$ vapor thermal conductivity (W/m-K) | σ liquid surface tension (10-3N/m) | $c_{p,\ell}$ liquid specific heat (kJ/kg-K) | $c_{p,v}$ vapor specific heat (kJ/kg-K) |
| 122 | 213 | 0.1591 | 237.95 | 1.474 | 0.9268 | 0.663 | 83 | 0.121 | 0.00656 | 20.8 | 1.223 | 0.692 |
| 123 | 233 | 0.5121 | 225.86 | 1.418 | 2.769 | 0.472 | 91.2 | 0.111 | 0.00817 | 17.6 | 1.255 | 0.749 |
| 124 | 253 | 1.3273 | 212.91 | 1.358 | 6.785 | 0.353 | 99.2 | 0.101 | 0.00982 | 14.51 | 1.293 | 0.816 |
| 125 | 273 | 2.928 | 198.6 | 1.295 | 14.428 | 0.271 | 107.3 | 0.092 | 0.01151 | 11.56 | 1.341 | 0.897 |
| 126 | 293 | 5.7171 | 182.28 | 1.225 | 27.778 | 0.211 | 115.81 | 0.0833 | 0.01333 | 8.76 | 1.405 | 1.001 |
| 127 | 313 | 10.166 | 163.02 | 1.147 | 50.075 | 0.163 | 125.5 | 0.0747 | 0.01544 | 6.13 | 1.498 | 1.145 |
| 128 | 333 | 16.818 | 139.13 | 1.053 | 81.413 | 0.124 | 137.9 | 0.0661 | 0.01831 | 3.72 | 1.66 | 1.387 |

Note that temp range is: T = 213 K – 333 K.

2. Now, the various properties are required as a function of T. So, the VBA program we write will search for the temp in the column B and if it finds the exact match, it will return the required property by reading the same in that row. If the exact temp match is not available (this is the more likely scenario), it will locate two consecutive cells where one temp is lower than required T, and the other temp is higher than T. Also, the corresponding values of the property at these two temperatures are noted. Then, a linear interpolation is made between these two values of the property and the same is returned.
3. Now, write the VBA code. Go to Developer – Visual Basic –

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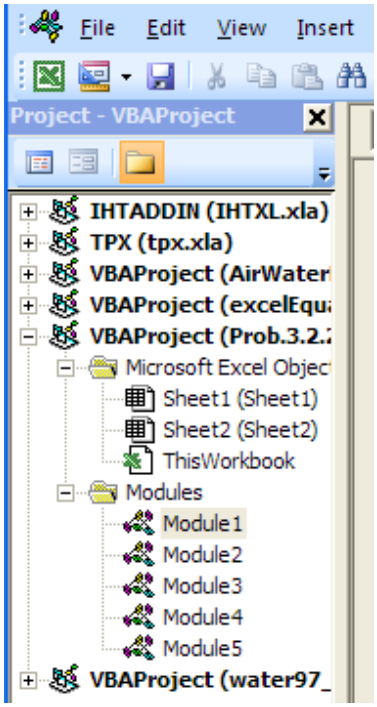
Click on Visual Basic:




And, click on Module1, wherein VBA programs for properties of Air, NH3 etc. were written. Go to the end of that Module and write programs for R134a.

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One example is shown below, for density of liquid, rho_f:

```
Function R_134a_rho_f_T(T As Double) As Double
'gives rho_f of R134a (kg/m^3)as a function of T (K) at sat. temp T(K)
'Reads rho_f values from Table and interpolates

Dim i As Integer

Dim T_1 As Double, T_2 As Double, rhof1 As Double, rhof2 As Double

If T < 213 Or T > 333 Then

 MsgBox ("T must be between 213 K and 333 K !!")

 End

End If

For i = 0 To 6

   If Cells(122 + i, 13) = T Then
       R_134a_rho_f_T = Cells(122 + i, 16) * 10 ^ 3
   End If
   If Cells(122 + i, 13) < T And Cells(122 + i + 1, 13) > T Then
      T_1 = Cells(122 + i, 13).Value
      T_2 = Cells(122 + i + 1, 13).Value
      rhof1 = Cells(122 + i, 16).Value
      rhof2 = Cells(122 + i + 1, 16).Value
      R_134a_rho_f_T = (rhof1 + (T - T_1) * (rhof2 - rhof1) / (T_2 - T_1)) * 10 ^ 3
   End If

Next i

End Function
```

In the above code:

1st line: declares name of the function, with dimensions of variables involved

Lines 2, 3: comments – explain about the Function

Line 4, 5: declarations of dimensions of internal variables, i.e. variables available only inside the Function

Line 6 to 9: If statement to give an error message if value of T entered is beyond the values available in the Table

Line 10: Beginning of For…Next construct. Note that the construct will search in the 7 lines of the Table

Lines 11, 12, 13: If the exact match for T is found, Function returns the value of 'rho' in the column P

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Lines 14 to 20: If he exact match of T is not there in the Table, then locate the values of T just below T and just above T,, and name them as T_1 and T_2. Also, note the corresponding values of rho as rhof1 and rhof2. And, then, calculate the value of rho at the required T by interpolation.

Line 21: Go to the next i in the loop

Line 22: End statement of Function.

4. Similar Functions are written for other properties of R134a, as functions of T. i.e.

For density of vap….R134a__rho_g_T(T)

For th. conductivity of liq….R134a_k_f_T(T)

For th. conductivity of vap….R134a_k_g_T(T)

For sp. heat of liq….R134a_cp_f_T(T)

For sp. heat of vap….SatNH3_cp_g_T(T)

For surface tension….R134a_sigma_f_T(T)

For dynamic viscosity of liq….R134a_mu_f_T(T)

For dynamic viscosity of vap….R134a_mu_g_T(T), and

For heat of vaporization of liq….R134a_hfg_T(T)

---

Now, using these VBA Functions for properties of R134a, we can write Functions for condensation of R134a on vertical plates, vertical cylinders, Horizl cylinder, Tube bank with horizl tubes in a vertical tier, condensation inside horizontal cylinder etc.

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One example of a VBA program for **condensation of R134a inside of a horizontal cylinder** is shown below:

```
Function Condensation_In_HCyl_R134a(T_sat As Double, T_s As Double, D As Double, L As Double, U_v As Double) As Variant

'Condensation of R134a at T_sat inside a Horizl Cylinder  held at T_s

'Input: T_sat, T_s (C), D, L (m), U_v (vap. velocity, m/s)

'Output: h_avg (W/m^2.C), Q (W) and mass_condensed (kg/s)

'Results are returned as an Array

Dim g As Double
Dim T_f As Double, h_fg As Double, rho_v As Double, mu_v As Double, Re_vap As Double

Dim rho_l As Double, mu_l As Double, nu_l As Double, k_l As Double, cp_l As Double, Pr_l As Double
Dim h_fg_prime As Double, h_avg As Double
Dim Q As Double, m_condensed As Double

If T_sat <= T_s Then
 MsgBox ("T_sat must be > T_s !")
 End
 End If

g = 9.81 '[m/s^2]
T_f = (T_sat + T_s) / 2 'Avg. temp.


 'Properties of liquid at Tf:

 rho_l = R_134a_rho_f_T(T_f + 273.15)
 mu_l = R_134a_mu_f_T(T_f + 273.15)
 cp_l = R_134a_cp_f_T(T_f + 273.15)
 k_l = R_134a_k_f_T(T_f + 273.15)
 nu_l = mu_l / rho_l
 Pr_l = cp_l * mu_l / k_l


 'Properties of vapour and h_fg at Tsat:

 rho_v = R_134a_rho_g_T(T_sat + 273.15)
 h_fg = R_134a_hfg_T(T_sat + 273.15)
 mu_v = R_134a_mu_g_T(T_sat + 273.15)


'Calculations:

h_fg_prime = h_fg + (3 / 8) * cp_l * _
(T_sat - T_s) 'modified h_fg....takes care of nonlinear temp distribn and liq film subcooling

Re_vap = rho_v * U_v * D / mu_v '..Vapour Reynolds No...must be < 35000!!

If (Re_vap <= 35000) Then

h_avg = 0.555 * ((g * rho_l * (rho_l - rho_v) * h_fg_prime * k_l ^ 3) / _
(mu_l * (T_sat - T_s) * D)) ^ (1 / 4) '[W/m^2-C] .... avg internal heat tr coeff over L

ElseIf (Re_vap > 35000) Then

    MsgBox ("Re_vap must be <= 35000. Now, Re_vap =" & Re_vap)

End If
```

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```
Q = h_avg * (Application.Pi() * D * L) * (T_sat - T_s) 'W

m_condensed = Q / h_fg_prime 'kg/s

Condensation_In_HCyl_R134a = Application.Transpose(Array(h_avg, Q, m_condensed))

End Function
```

Now, the above program is an Array Function and returns h_avg, Q and Mass_condensed inside a horizontal cylinder.

**Let us solve a problem using this Function:**

**Prob. 3.2.30.** Sat. R134a vapour at 30 C condenses inside a horizontal tube of 1 cm ID, 5 m long and the tube surface is maintained at 20 C. Determine: (a) rate of heat transfer (b) rate of condensation of R134a. Assume that the entering vapour has negligible velocity (i.e. U_v = 0).

**EXCEL Solution:**

We shall use the VBA Function for condensation of R134a inside a horizontal cylinder, written above.

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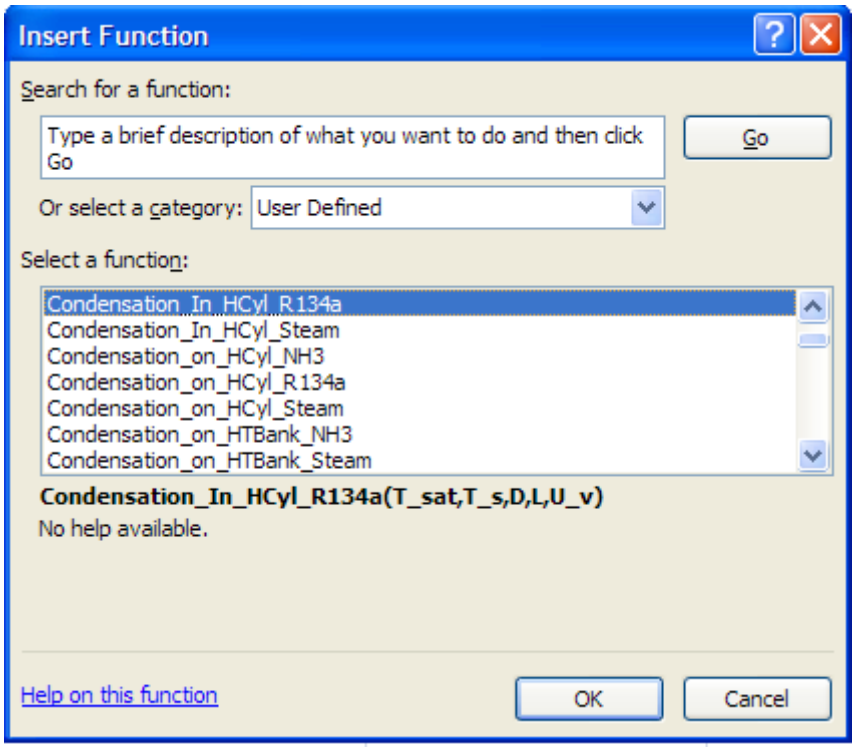
1. Set up the EXCEL worksheet for this problem. Remember that the Function we are going to use is an Array Function:

C526 =C525*3600

| | A | B | C | D |
|---|---|---|---|---|
| 514 | | | | |
| 515 | | Data: Fluid: R134a | | |
| 516 | | T_sat | 30.00 | C |
| 517 | | T_s | 20.00 | C |
| 518 | | D | 0.01 | m |
| 519 | | L | 5.000 | m |
| 520 | | U_v | 0.0 | m/s |
| 521 | | | | |
| 522 | | | | |
| 523 | | h_avg | | W/m^2.C |
| 524 | | Q | | W |
| 525 | | m_cond | | kg/s |
| 526 | | m_cond_per_hour | 0.000 | kg/h |

2. Select the cells C523 to C525 and select the Array Function for condensation of R134a inside a horizontal cylinder from the 'User Defined' category:

We have:

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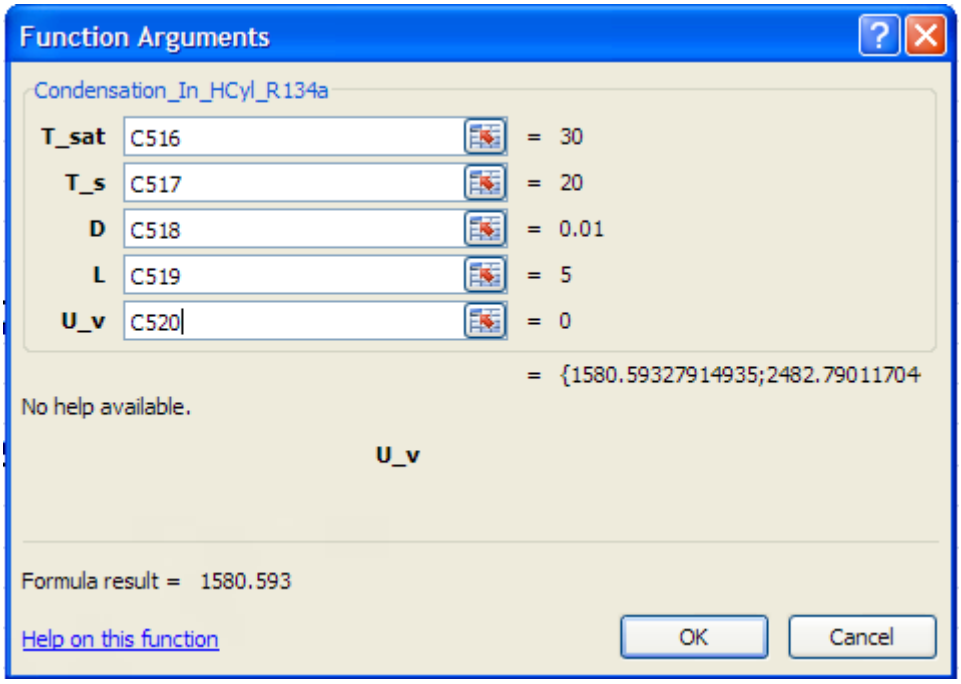
Click OK. We get the following screen. Fill it up as shown:



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Press (Ctrl+Shift+OK) since it is an Array Function, and we get:

C525 {=Condensation_In_HCyl_R134a(C516,C517,C518,C519,C520)}

| | A | B | C | D |
|---|---|---|---|---|
| 514 | | | | |
| 515 | | Data: Fluid: R134a | | |
| 516 | | T_sat | 30.00 | C |
| 517 | | T_s | 20.00 | C |
| 518 | | D | 0.01 | m |
| 519 | | L | 5.000 | m |
| 520 | | U_v | 0.0 | m/s |
| 521 | | | | |
| 522 | | | | |
| 523 | | h_avg | 1580.593 | W/m^2.C |
| 524 | | Q | 2482.790 | W |
| 525 | | m_cond | 0.013959 | kg/s |
| 526 | | m_cond_per_hour | 50.252 | kg/h |

**Thus:**

**h_avg = 1580.59 W/m^2.C …. Ans.**

**Q = 2482.79 W …. Ans.**

**m_cond_per_hour = 50.252 kg/h …. Ans.**

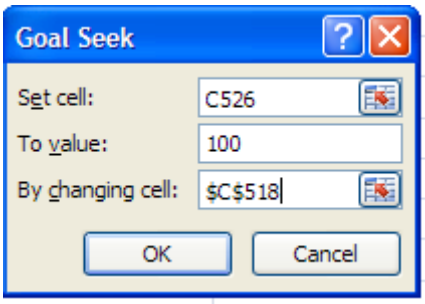
---

**(b) What should be the diameter if we need to have a condensation rate of 100 kg/h?**

This is easily calculated by applying Goal seek to cell C526 (i.e. m_cond_per_hour) to make it equal to 100 by changing cell C518 (i.e. D).

The procedure is:

Go to Data-WhatIf Analysis- Goal Seek Click on Goal Seek. We get the following screen; fill it up as shown:

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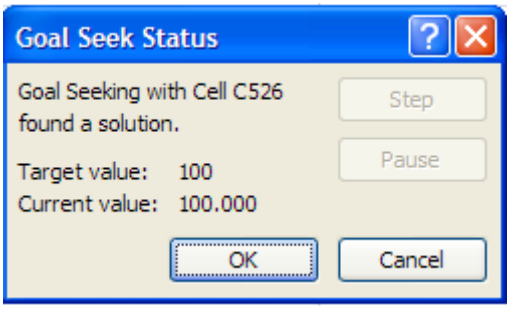
Click OK. We get:




Goal Seek has found a solution. Again, click OK and see the result in cell C518:

C518 | 0.0250299248479914

| | A | B | C | D |
|---|---|---|---|---|
| 514 | | | | |
| 515 | | Data: Fluid: R134a | | |
| 516 | | T_sat | 30.00 | C |
| 517 | | T_s | 20.00 | C |
| 518 | | D | 0.03 | m |
| 519 | | L | 5.000 | m |
| 520 | | U_v | 0.0 | m/s |
| 521 | | | | |
| 522 | | | | |
| 523 | | h_avg | 1256.624 | W/m^2.C |
| 524 | | Q | 4940.657 | W |
| 525 | | m_cond | 0.027778 | kg/s |
| 526 | | m_cond_per_hour | 100.000 | kg/h |

**Thus: Value of D required to get a condensation rate of 100 kg/h = 0.03 m … Ans.**

**Note that correspondingly, values of h_avg and Q also have changed.**

==========

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# References

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3. F.P. Incropera and D.P. DeWitt, *Fundamentals of Heat and Mass Transfer*, 5th Ed., John Wiley & Sons.
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